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Thermal Treatment of Municipal Sewage Sludges

Los Angeles County Sanitation Districts
Whittier, CA

Prepared for

Municipal Environmental Research Lab.
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THERMAL TREATMENT OF MUNICIPAL SEWAGE SLUDGES

by

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Contract No. 14-12-150

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16. ABSTRACT

The thermal conditioning research program was conducted as part of an overall long-term sludge management study for the Los Angeles and Orange County metropolitan areas. The major goal of this portion of the study was to investigate the advantages of thermal conditioning of primary and waste activated sludges prior to anaerobic digestion, on a continuous flow and pilot scale basis. The studies were designed to demonstrate whether thermal conditioning would help produce increased gas production and volatile solids destruction during subsequent anaerobic stabilization of the sludge. Anaerobic digestion and anaerobic filtration were used for sludge stabilization. The effects of thermal conditioning on sludge dewaterability were studied by means of dewatering via a filter press, vacuum filter, scroll and basket centrifuges and belt filter press. Other studies of interest included the fate of pathogens and heavy metals, and the production and control of odors during the thermal conditioning process.

The pilot scale thermal conditioning unit was tested using a variety of operational conditions. Operating temperatures and pressures were varied and thermal conditioning with and without the use of oxygen was investigated. Two types of wastewater sludges were used: waste activated sludge and a blend of 65 percent raw primary and 35 percent waste activated sludge. An energy analysis was conducted to determine the net energy demands of including thermal conditioning in the sludge process.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents design details, operating experiences, and operating and performance data for operation of a thermal conditioning system for municipal sewage sludges prior to anaerobic digestion. Results of further processing such as digestion, mechanical dewatering, and composting of the thermally conditioned sludge are included. Consideration of the operational results presented herein is recommended for design engineers, facility planners, and potential municipal users of a sludge thermal conditioning system.

Francis T. Mayo
Director
Municipal Enviromental
Research Laboratory

ABSTRACT

The thermal conditioning research program was conducted as part of an overall long-term sludge management study for the Los Angeles and Orange County metropolitan areas. The major goal of this portion of the study was to investigate the advantages of thermal conditioning of primary and waste activated sludges prior to anaerobic digestion, on a continuous flow and pilot scale basis. The studies were designed to demonstrate whether thermal conditioning would help produce increased gas production and volatile solids destruction during subsequent anaerobic stabilization of the sludge. Anaerobic digestion and anaerobic filtration were used for sludge stabilization. The effects of thermal conditioning on sludge dewaterability were studied by means of dewatering via a filter press, vacuum filter, scroll and basket centrifuges and belt filter press. Other studies of interest included the fate of pathogens and heavy metals, and the production and control of odors during the thermal conditioning process.

The pilot scale thermal conditioning unit was tested using a variety of operational conditions. Operating temperatures and pressures were varied and thermal conditioning with and without the use of oxygen was investigated. Two types of wastewater sludges were used: waste activated sludge and a blend of 65% raw primary and 35% waste activated sludge. An energy analysis was conducted to determine the net energy demands of including thermal conditioning in the sludge process.

This report was submitted in fulfillment of Grant Amendment C-06-1051-014, by the County Sanitation Districts of Los Angeles County, California, under the sponsorship of the California State Water Resources Control Board and the U.S. Environmental Protection Agency (EPA). Additional funding was received from the EPA Office of Research and Development under Contract No. 14-12-150. This report covers the project period of September 1975 through November 1980.

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SECTION 1

INTRODUCTION

In August 1976, a pilot scale investigation of the thermal pretreatment-anaerobic digestion process was initiated at the Joint Water Pollution Control Plant (JWPCP) in Carson, California. The specific objectives of these studies were: 1) to demonstrate on a continuous flow, pilot scale basis the concept of thermal treatment of primary and waste activated sludge prior to anaerobic digestion; 2) to determine the potential for increased methane production as a result of thermal pretreatment; 3) to determine the dewatering properties of the digested sludge; 4) to identify operational problems in the system; 5) to determine the effectiveness of a water scrubber-carbon adsorption system for the control of odorous off-gases; 6) to develop design and operating parameters for a full-scale system; 7) to develop energy balances for the entire system and, 8) to demonstrate the treatment of thermally treated decant liquors with an anaerobic filter. Earlier laboratory studies (at Stanford University) indicated that there were potential toxicity problems in digesting sludges that had been thermally conditioned at temperatures above 177°C (350°F). This question was also to be resolved in this pilot scale testing program.

This demonstration project was divided into three phases. The specific flow scheme investigated under Phase I incorporated thermal treatment of flotation thickened waste activated sludge followed by: 1) thermophilic anaerobic digestion and mechanical dewatering; or 2) decant separation of the thermally conditioned sludge with anaerobic filtration of the supernatant and mechanical dewatering of the subnatant. Phase II was identical to Phase I except that a blend of waste activated and primary sludge served as the feed to the thermal conditioning unit. A sludge blend of 65% raw primary and 35% waste activated sludge (WAS) was used to approximate the projected ratio at the JWPCP when full-scale secondary treatment is implemented. Phase III incorporated thermal treatment of thickened WAS followed by decant separation (thickening) of the sludge with anaerobic digestion of the supernatant and mechanical dewatering of the subnatant. Phase III was conducted primarily to study odor control techniques and to test a two-stage odor control system for decant tank off-gases.

The intent of this report is to present a summary of the field data collected during each phase of the study and to present information on each system to permit development of design criteria. This report will also present energy balances for each of the operating conditions that are sufficiently accurate for use in a preliminary design. Valid data on the traditional problems of thermal conditioning could not be developed during

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this study. The pilot unit was designed for demonstration purposes and therefore was capable of handling a wide variety of sludges under a number of different operating modes. The thermal efficiency of the test unit was not representative of a well-designed full-scale system. Problems regarding corrosion and fouling of the heat exchangers were not addressed. The mechanical reliability of the test unit was relatively poor and the age of the test unit, its design for flexibility in handling a wide variety of sludges, and the space limitations inside the trailer made comparisons with a modern, single purpose unit very difficult.

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SECTION 2

CONCLUSIONS

Significantly improved energy efficiency can result if thermal conditioning is performed prior to anaerobic digestion rather than after digestion. The major variable is the efficiency of the heat exchangers in the thermal conditioning unit. If the efficiency is high enough, the thermal pretreatment-anaerobic digestion system could result in a net surplus of energy. Advantages of thermal conditioning prior to digestion (rather than after digestion) appear to be: 1) stable digestion with less degradable organic recycle to the wastewater treatment plant, 2) greater methane gas recovery, 3) more positive control of odors, and 4) a reduced quantity of solids for ultimate disposal. Advantages of the conventional thermal conditioning system (after digestion) with anaerobic treatment of liquid side streams include: 1) slightly drier cake solids following dewatering, and 2) reduced polymer conditioning requirements. Selection of the final mode of operation will likely depend on site specific factors and the ultimate disposition of the solids. It should be noted that any type of thermal treatment results in a significantly smaller net energy surplus than if the sludge were to receive anaerobic digestion alone.

During the 17 months of operation of the thermal conditioning system, thermophilic anaerobic digestion of the thermally conditioned WAS proved very reliable. No toxicity problems or digester upsets occurred and digestion performance was not significantly affected by the temperature of thermal pretreatment over the range of temperatures from 170 to 220°C (340° to 425°F). The thermal pretreatment - anaerobic digestion system increased volatile solids destruction by 65% over standard mesophilic digestion and 36% over standard thermophilic digestion. When taking into account only those volatile solids destroyed in the digester, the percent increases dropped to 40 and 15% respectively over standard mesophilic and thermophilic digestion of WAS. Thermal pretreatment and thermophilic digestion of the 65% primary/35% WAS blend did not produce results significantly different from standard thermophilic digestion.

Thermal conditioning with temperatures in excess of 150°C (300°F) for about 30 min, should assure the complete destruction of all pathogenic microorganisms. Data indicated that viable parasitic helminth ova were essentially eliminated from the digested sludge and bacterial groups were significantly reduced compared to standard digester effluent. Regrowth of coliform organisms and, in some cases, Salmonella sp. were observed on occasion (possibly due to poor temperature distributions in the thermal

conditioning unit). However, salmonellae concentrations remained lower than those in standard digester effluent.

Thermally conditioned, digested sludges dewatered well compared to sludges receiving anaerobic digestion alone. Filtration devices were generally more effective than centrifugal devices in dewatering these sludges. However, prethickening of sludge was a necessary step before vacuum or pressure filtration to attain acceptable cake consistency and discharge characteristics. The mixture of primary and WAS had slightly better dewatering characteristics than WAS alone. Test runs using thermally conditioned undigested sludges indicated that dewatering characteristics are degraded slightly by subsequent digestion. Cake solids concentrations are lowered and polymer doses are increased. Thermal conditioning of WAS at temperatures above 190°C (380°F) was found to be necessary to produce successful dewatering.

A two-stage water scrubber - carbon adsorption unit was successful in removing 97% of the odor concentration from the thermal conditioning decant tank exhaust gases. Alone, the water scrubber portion was able to remove about 68% of the exhaust gas odor concentration.

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SECTION 3

PILOT SCALE THERMAL PRETREATMENT AND STABILIZATION

INTRODUCTION

A trailer-mounted continuous flow thermal conditioning pilot plant was leased from Zimpro Inc. and served as the thermal pretreatment system for these studies. A schematic of the process is shown in Figure 1. Feed sludge passes through a grinder to reduce all particles to 0.8 cm (0.3 in) dimensions before pumping. Sludge and air, when operating under low pressure oxidation, are then pumped to the thermal pretreatment system. The sludge, with or without air, is then passed through heat exchangers and brought to the initial reaction temperature as it enters the reactor. Oxidation takes place within the reactor, and the oxidized products leaving the reactor are cooled in the heat exchangers against the entering cold sludge. Steam is added directly to the reactor for start-up, and whenever the process is not thermally self-sustaining.

Thermal conditioning results in significant changes in the nature and composition of wastewater sludge. The high temperatures and pressures breakdown the cellular material found in sludge, especially waste activated sludges. Cell walls are ruptured, releasing the protoplasm; proteinaceous matter and the external cellular slime layer are also broken down. The solubilized matter includes ammonia nitrogen and volatile acids plus many other organic compounds. The resulting dark brown liquor is very high in COD and has a persistent and pungent odor. The cell walls and other solid debris remain in solution and the dewatering characteristics of the remaining solids are vastly improved. A percentage of the influent COD is oxidized by this process if air is added to the reactor.

During these studies, the thermal conditioning unit was operated under two modes: heat treatment (HT) and modified low pressure oxidation (LPO). The term "modified" is used here because under normal LPO conditions enough oxygen is added to the thermal reactor to oxidize 5 to 10% of the influent COD. Realizing that one of the main objectives of these thermal pretreatment studies is to maximize gas production upon subsequent digestion, COD oxidation through the pretreatment facility must be kept to a minimum. To minimize the oxidation of organics through the thermal reactor, the quantity of air supplied was decreased from 4.7 to 7.1 liter/s (10 to 15 scfm) for normal LPO conditions to 0.6 liter/s (1.2 scfm) under modified operation. The theoretical degree of COD oxidation under these modified conditions approximates one percent and should not significantly affect methane production when the sludge is anaerobically digested. The small

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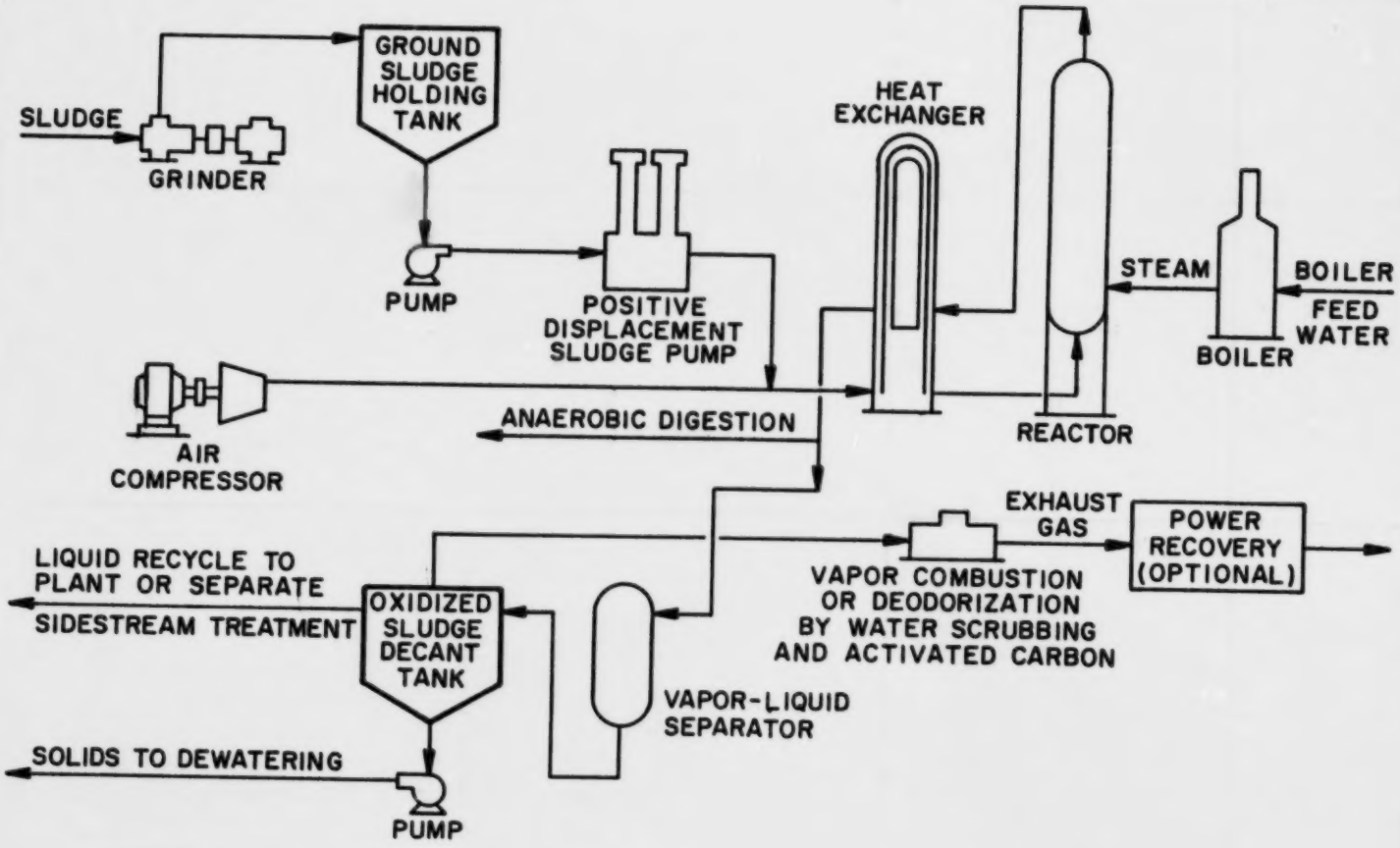


Figure 1. Schematic diagram of the Zimpro thermal conditioning process.

amount of air still provides an oxidizing environment in the reactor and the conditioned sludge should behave in a similar manner to sludge that receives normal LPO conditioning.

Pilot scale anaerobic digestion studies were carried out in a 45-m^3 (12,000 gal) single stage digester equipped with a gas recirculation system for mixing and heat exchangers to maintain thermophilic temperatures. Anaerobic filtration studies were conducted on a 1.2-m (4 ft) diameter by 3-m (10 ft) high filter. A diagram of the filter is presented in Figure 2. Feed was introduced at the top through a 1.9-cm (0.75 in), 120° spray nozzle. The filter was loaded with three 0.6-m (2 ft) deep sections of B,F. Goodrich plastic media with a unit of 144 m^2/m^3 (44 ft^2/ft^3). To reduce the possibility of short circuiting along the wall of the filter, a 1.9-cm (0.75 in) wide rubber gasket was installed between the media sections and glued securely against the inner surface of the filter wall. The filter was kept at thermophilic inner surface temperatures by means of a hot water piping system attached to the outer wall of the filter.

This study was conducted in three phases as discussed in the introduction. A general schematic of the sludge processing pilot facilities is presented in Figure 3. During each phase of testing, data were collected on thermal conditioning, anaerobic digestion and filtration, and mechanical dewatering of various sludge blends. Studies were also conducted on odor control and composting. Results from each phase of testing are presented below.

PHASE I

During Phase I studies, only dissolved air flotation thickened WAS was used for a feed. The thermal conditioning unit was operated in both heat treatment and modified low pressure oxidation modes. Both modes were followed by thermophilic anaerobic digestion and mechanical dewatering or decant separation of the thermally conditioned sludge with anaerobic filtration of the supernatant and mechanical dewatering of the subnatant (Figure 3).

Heat Treatment Conditioning of WAS

Thermal pretreatment of waste activated sludge under heat treatment conditions was conducted from August 12, 1976 to November 15, 1976. The thermal reactor operating temperatures maintained during the initial investigations varied from 170° to 190°C (340° to 370°F) and were considerably lower than those maintained during previous thermal treatment studies. These lower temperatures were selected because of toxicity encountered in subsequent digestion of heat treated sludge during lab scale investigations at Stanford University(1). In that study, thermal pretreatment temperatures in excess of 175°C (350°F) resulted in unsteady digester operation. Due to poor dewatering properties of the conditioned sludge,

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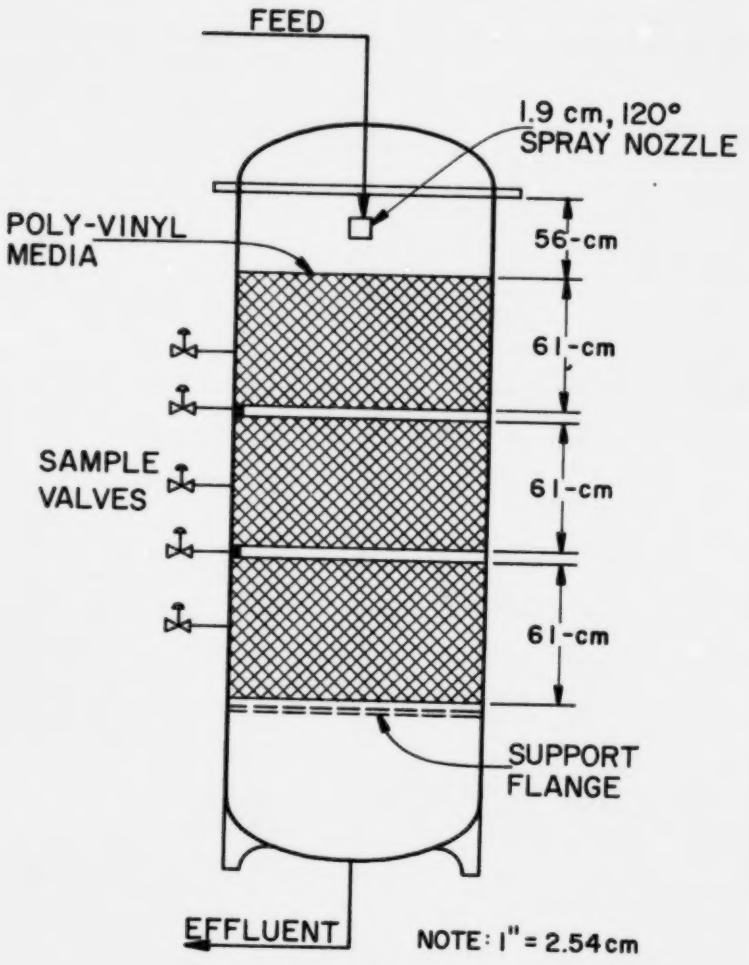


Figure 2. Schematic diagram of the pilot-scale anaerobic filter.

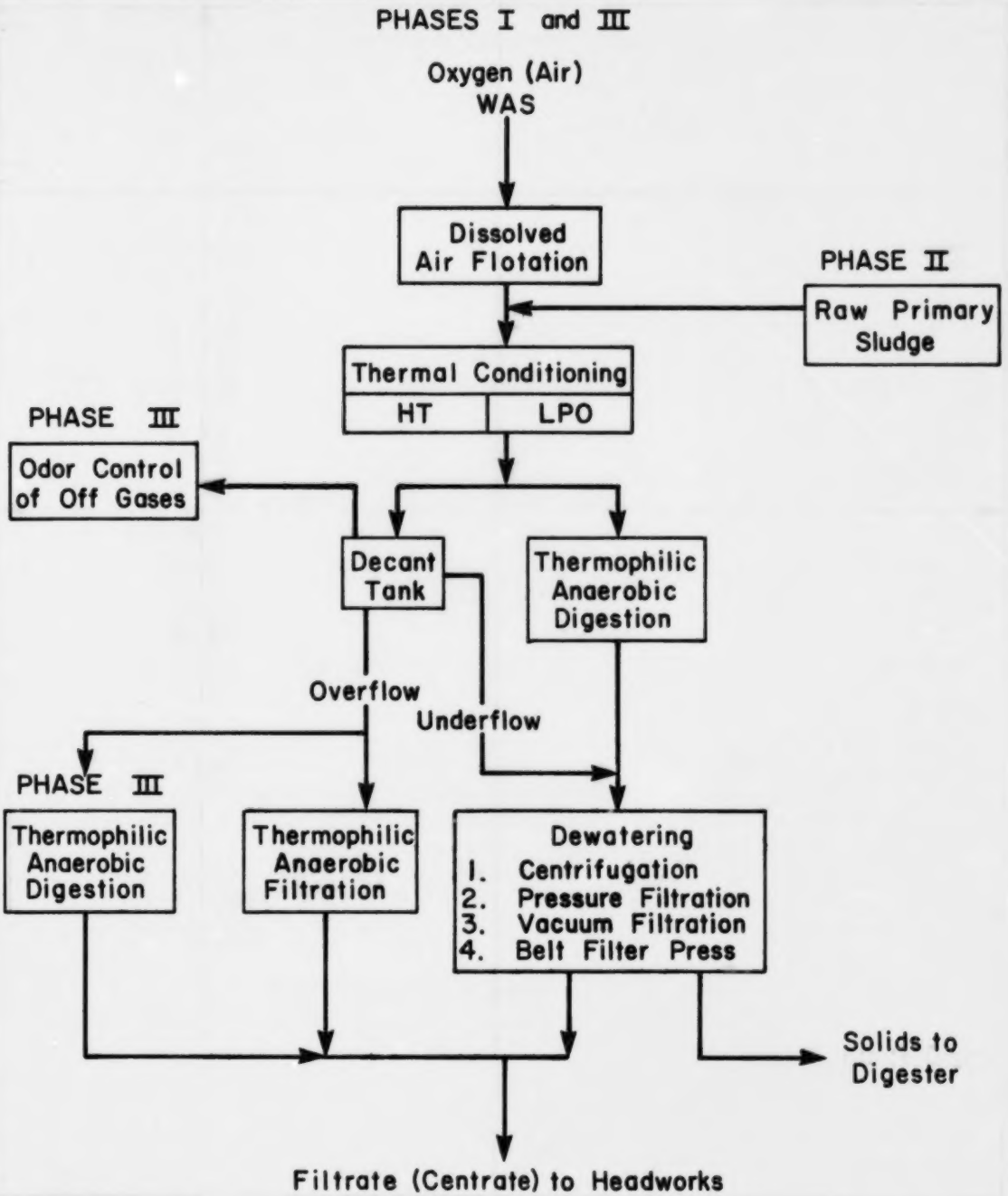


Figure 3. Schematic diagram of the sludge processing pilot facility.

TABLE 1. DIGESTER RESPONSE TO HEAT TREATED WAS FROM AUG. 12 - SEPT. 20, 1976

PERFORMANCE	Units	Total System	Digestion
VS Destruction	kg/day(lb/day)	21.3 (46.9)	15.4 (34.0)
VS Destruction	%	51.3	43.3
COD Removal	%	35.8	28.8
Gas Production	m^3/kg (ft^3/lb) VS destroyed	0.68 (10.9)	0.94 (15.0)
Methane Production	m^3/kg (ft^3/lb) COD destroyed	0.44 (7.1)	0.60 (9.7)
OPERATING PARAMETERS			
Digester Volume	m^3(gal)	--	45.4 (12,000)
Average Feed Rate	m^3/day (GPD)	--	1.7 (441)
Hydraulic Detention Time	days	--	27.2
VS Loading	kg/m^3/day(lb/ft^3/day)	0.91(0.057)	0.78 (0.049)
Gas Production	m^3/day(ft^3/day)	14.4(509)	14.4 (509)
Methane Content	%	61.5	61.5
Temperature	°C(°F)	--	49(120)

Constituents		Influent	Heatrate**	Effluent
pH		6.53	6.21	7.68
Total Solids	%	3.59	2.80	2.00
Volatile Solids	%TS	77.6	76.3	60.7
Total Dissolved Solids	mg/l	--	10,800	3,050
Fixed Solids	kg/day(lb/day)	12.0(26.5)*	11.1(24.4)	13.1(28.9)
Alkalinity	mg/l	820	770	4,870
Volatile Acids	mg/l	--	--	109
Chloride	mg/l	396	354	--
Total COD	mg/l	33,500*	30,200	21,500
Soluble COD	mg/l	2,270*	12,500	3,090
Coliforms	MPN/100 ml	--	--	--
Fecal Coliforms	MPN/100 ml	--	--	--
Total Kjeldahl Nitrogen	mg/l	2,006	1,957	2,420
Ammonia Nitrogen	mg/l	86	323	1,550

*Corrected for steam dilution
**A "coined" term to indicate the effluent from the thermal treatment unit.

Thermal Reactor Parameters

Temperature: 170-190°C (340-370°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.0 l/s (scfm)

the temperature of the thermal reactor was increased to 200°C (400°F) on September 21, to observe its effect on digestion and subsequent dewaterability.

Stabilization: Anaerobic Digestion --

The operation of the entire sludge stabilization system while pretreating under heat treatment conditions is summarized in Tables 1 and 2. Figure 4 chronologically plots the digester response (gas production, gas composition, and volatile acids) following thermal conditioning.

TABLE 2. DIGESTER RESPONSE TO HEAT TREATED WAS FROM OCT. 1 - NOV. 14, 1976

PERFORMANCE	Units	Total System	Digestion
VS Destruction	kg/day(lb/day)	17.4 (38.4)	12.0 (26.5)
VS Destruction	%	52.2	43.0
COD Removal	%	39.4	36.8
Gas Production	m^3/kg (ft^3/lb) VS destroyed	0.65 (10.5)	0.95(15.2)
Methane Production	m^3/kg (ft^3/lb) COD removed	0.37 (5.9)	0.41(6.6)
OPERATING PARAMETERS			
Digester Volume	m^3(gal)	--	45.4 (12,000)
Average Feed Rate	m^3/day (GPD)	--	1.6 (423)
Hydraulic Detention Time	days	--	28.4
VS Loading	kg/m^3/day(lb/ft^3/day)	0.74(0.046)	0.61 (0.038)
Gas Production	m^3/day(ft^3/day)	11.4(403)	11.4 (403)
Methane Content	%	62.5	62.5
Temperature	°C(°F)	--	49 (120)

Constituents		Influent	Heatrate **	Effluent
pH		6.55	5.73	7.66
Total Solids	%	3.28	2.33	1.85
Volatile Solids	%TS	75.8	74.8	53.8
Total Dissolved Solids	mg/l	2,020	12,900	3,520
Fixed Solids	kg/day(lb/day)	10.7(23.5)*	9.3(20.5)	(30.2)
Alkalinity	mg/l	770	683	5,120
Volatile Acids	mg/l	490	643	260
Chloride	mg/l	360	293	--
Total COD	mg/l	30,400*	29,100	18,400
Soluble COD	mg/l	1,030*	15,700	3,880
Coliforms	MPN/100 ml	2.3×10^7	<300	<300
Fecal Coliforms	MPN/100 ml	--	--	--
Total Kjeldahl Nitrogen	mg/l	2,280	1,930	2,220
Ammonia Nitrogen	mg/l	99	305	1,550

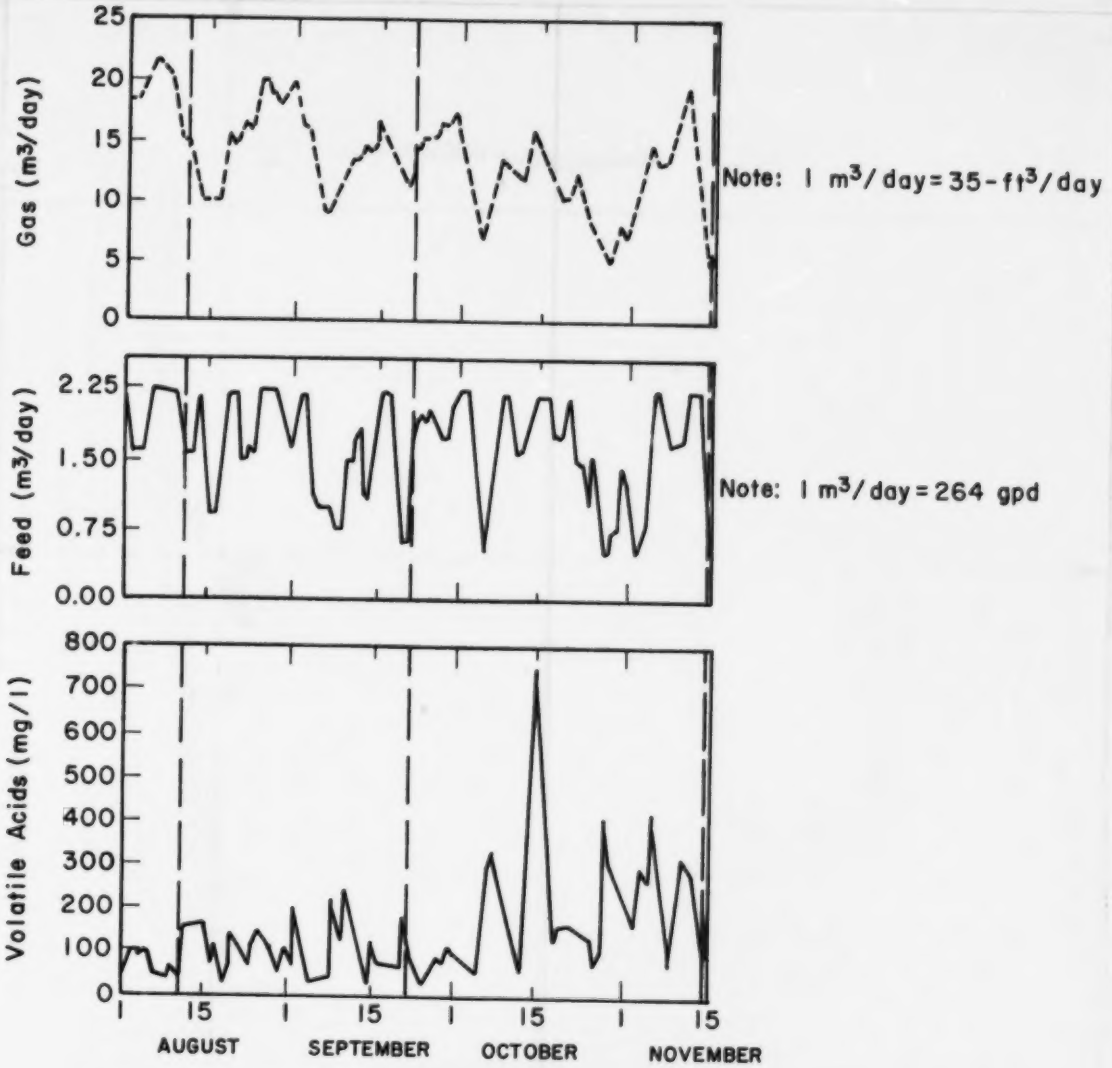
*Corrected for steam dilution

**Heatrate - a "coined" term to indicate the effluent from the thermal treatment unit.

Thermal Reactor Parameters

Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.0 l/s (scfm)

Included in Figure 4 are the thermal conditioning operating parameters and the daily sludge feed for the 45-m^3 (12,000-gal) digester. In Tables 1 and 2, the complete thermal conditioning unit-anaerobic digester system is presented as a single system. The influent corresponds to the thickened waste activated sludge being fed to the thermal conditioning unit. The heatrate is the thermally conditioned sludge as it exists in the thermal reactor; including both the solids and liquid fractions of the sludge. The heatrate is also the feed to the digester. The effluent data corresponds



THERMAL CONDITIONING UNIT OPERATING PARAMETERS

	Aug. 12–Sept. 20	Oct. 1–Nov. 14
Temperature	170–190°C (340–370°F)	200°C (400°F)
Pressure	28 kgf/cm^2 (400 psi)	28 kgf/cm^2 (400 psi)
Detention Time	29 min.	29 min.

Figure 4. Digester response to heat treated WAS.

to the discharge from the anaerobic digester. Table 1 summarizes the system performance for heat treatment temperatures of 170° to 190°C (340° to 370°F) while Table 2 reflects the system performance at a pretreatment temperature of 200°C (400°F).

As the thermal pretreatment study began, the pilot digester was already in operation. Studies were being conducted on digesting thickened waste activated sludge. The feed to the the digester was changed to heat treated sludge as soon as this study was initiated. It is important to note that there were no operational or toxicity problems encountered during this transition.

Table 1 data indicate the system's performance when the temperatures in the heat treatment conditioning process ranged from 170° to 190°C (340° to 370°F). The data in Table 1 include the average digester effluent characteristics during this transition phase. The reporting period of August 12 to September 21 is only equal to 1.5 hydraulic detention times. Since the thermal reactor temperatures were also being changed, the digester performance data in Table 1 should be used only to demonstrate that digestion of a thermally pretreated sludge is feasible. The influent and heatrate chloride data in Table 1 are presented to indicate the dilution factor that results from steam addition to the thermal reactor. Chloride is a conservative substance unaffected by the operating temperatures and pressures. Any change between the influent and heatrate concentration values is caused by the addition of steam. The influent volatile solids mass data and the influent COD concentrations have been corrected for steam dilution. Thus, comparisons can be made directly between influent values and heatrate values in order to show volatile solids destructions and COD removals. Corrections were not made to the heatrate values because no further dilution occurs between the heat unit outlet and the digester inlet.

Data in Table 1 show that the digester was providing volatile solids destruction and COD removals. Gas production was measured at 0.94 m^3/kg (15 ft^3/lb) of volatile solids destroyed. Volatile acids concentration and ammonia nitrogen concentrations in the digester effluent indicate stable operation and no toxicity. Since no air was added to the sludge in the thermal conditioning unit, there should not have been any COD removals. It is felt that the indicated COD removals were really due to use of soluble chloride concentration values to measure steam dilution. In future tests, total chloride values were used.

The relatively low temperature heat treatment studies were terminated after only 32 days of operation because of poor sludge dewatering characteristics. As will be discussed later in greater detail, previous heat treatment studies(2) conducted at temperatures above 190°C (370°F), resulted in a sludge with superior dewatering properties.

On September 21, 1976 the temperature of the thermal reactor was increased to 200°C (400°F) while the operating pressure and detention time remained at 2758 kPa (400 psi) and 29 min respectively (Tables 1 and 2).

The heat treatment-anaerobic digestion system performance data are shown in Table 2 for a 45-day period or 2 hydraulic detention times. Six composite samples of the thermal conditioning unit influent and heatrate steams were taken and analyzed for total chloride concentration. The influent concentration averaged 360 mg/l while the heatrate concentration averaged 293 mg/l. The reduction in chlorides across the reactor was measured at 18.6%, indicating that for every cubic meter of sludge processed, 0.23 m^3 of boiler make-up water were required. Influent COD concentration and volatile solids mass data presented in Table 2 have been adjusted for steam dilution based on the difference in influent and heatrate chloride data.

During this period, the digester received an average flow of 1.6 m^3/day (423 gpd) of thermally treated sludge and condensed steam resulting in a detention time of 28 days. The volatile acid concentration increased slightly from that reported, while pretreating at 170° to 190°C (340° to 370°F), but the digester continued to operate in a stable fashion. The toxicity effects noted at Stanford(1), when thermal conditioning temperatures were above 175°C (350°F), were not encountered during this period. No significant differences were observed in the digester performance between pretreatment temperatures of 170° to 190°C (340° to 370°F) and 200°C (400°F).

Anaerobic Filtration --

No data can be reported on the anaerobic filtration of decant liquors from heat treated waste activated sludge. Studies were started in late October 1976 but a variety of operational problems prevented steady-state operations until after the thermal conditioning unit was changed to the LPO mode.

Mechanical Dewatering --

Vacuum and pressure filtration tests were conducted on thermally conditioned waste activated sludge both before and after digestion. Other devices were not available for dewatering at this time. The undigested sludge was taken as underflow from the gravity decant tank and the solids had concentrated to 8 to 10%. The dewatering data for the low temperature heat treatment sludge are presented in Tables 3 and 4; data from the 200°C (400°F) heat treatment tests are shown in Tables 5 and 6. These tables include data on machine size, operational parameters, etc.

The low temperature heat treated sludge did not display good dewatering characteristics. One filter press run was made on the undigested heat treated sludge; the results in Table 3 show only a 24% cake was produced. The filter yield was relatively poor at 2.0 kg/m^2/hr (0.40 lb/ft^2/hr). The qualitative judgement regarding poor cake discharge and poor consistency were based on the nature of the cake. The outer portions of the cake were dry but the inner portion of the cake was liquid in nature. The cake did not discharge from the cloth and had to be manually scraped from the fabric. Extensive washing of the fabric was required before the next test. When comparing this data with previous dewatering data collected at the JWPCP(2), it becomes apparent that thermal pretreat-

TABLE 3. PRESSURE FILTRATION OF HEAT TREATED WAS (170°-190°C)

Sludge Type	Filter Yield[a] kg/m²/hr (lb/ft²/hr)	Cycle Time min.	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Discharge
Thickened Heatrate	1.95 (0.40)	90	8.40	7.46	0.992	0.052	99.3	24.3	Poor
Digested Heatrate	(b)	120	2.16	1.67	1.063	0.578	65	8.7	Very Poor
Conditioned[c] Digested Heatrate	0.68 (0.14)	135	1.96	1.67	0.322	0.032	98.1	15.6	Poor

[a]Cloth Medium: 1-P

[b]No mass balance attempted-yield not calculated

[c]760gCaO/kg sludge (1520 lb/ton)
160g$FeCl_3$/kg sludge (320 lb/ton)

Thermal Reactor Parameters
Temperature: 170-190°C (340-370°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min.
Air: 0.0 l/s (scfm)

Digester Parameters
Temperature: 49°C (120°F)
Detention Time: 27 days

TABLE 4. VACUUM FILTRATION OF HEAT TREATED WAS (170°-190°C)

Sludge Type	Run #	Filter Yield[a] kg/m²/hr (lb/ft²/hr)	Cycle Time min:sec	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Discharge
Digested[b] Heatrate	1	1.32 (0.27)	4:09	2.23	1.95	0.418	0.138	92.9	21.7	Very Poor
Digested[c] Heatrate	2	1.61 (0.33)	4:09	2.23	1.95	0.369	0.089	95.4	20.9	Very Poor

[a]Cloth Medium: KS-515

[b]$FeCl_3$ Dosage: 123 g/kg (246 lb/ton)
Lime Dosage: 515 g/kg (1,030 lb/ton)

[c]$FeCl_3$ Dosage: 178 g/kg (356 lb/ton)
Lime Dosage: 776 g/kg (1,552 lb/ton)

Thermal Reactor Parameters
Temperature: 170-190°C (340-370°F)
Pressure: 2758 kPa (400psig)
Detention Time: 29 min
Air: 0.0 l/s (scfm)

Digester Parameters
Temperature: 49°C(120°F)
Detention Time: 27 days

ment temperatures must be maintained above 190°C (370°F) for successful filtration of the resultant sludge.

Digestion of the low temperature heat treated sludge resulted in degraded dewatering characteristics. Table 3 data show that unless large amounts of conditioning chemicals are added, the filter press cannot dewater the digested sludge. Even with the addition of 75% lime and 16% ferric chloride, the cake from the filter press had only 15.6% solids; filter yields were very poor at 0.68 kg/m²/hr (0.14 lb/ft²/hr). Cake consistency and discharge from the filter fabric were poor.

TABLE 5. PRESSURE FILTRATION OF HEAT TREATED WAS (200°C)

Sludge Type	Run #	Filter Yield[a] $kg/m^2/hr$ ($lb/ft^2/hr$)	Press Time min	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Consistency/ Discharge
Thickened Heatrate	4	4.30 (0.88)	90	9.89	9.02	0.88	0.012	99.9	44.3	Good/ Fair
Thickened Heatrate	5	5.37 (1.10)	65	9.98	9.02	0.88	0.012	99.9	39.6	Fair-Good/ Fair
Digested Heatrate	6	(b)	130	1.99	1.46	-	0.040	97.3	(b)	Very poor/ Very Poor
Conditioned[c] Digested Heatrate	7	0.78 (0.16)	120	1.99	1.46	-	0.008	99.4	28.6	Poor-Fair/ Poor

[a] Cloth Medium: 1-P

[b] No samples due to very poor cake quality.

[c] 750g CaO/kg sludge (1500 lb/ton)
150g $FeCl_3$/kg sludge (300 lb/ton)

Thermal Reactor Parameters
Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.0 l/s (scfm)

Digester Parameters
Temperature: 49°C (120°F)
Detention Time: 28 days

The vacuum filter performance on digested, low temperature heat treated sludge was also very poor. Table 4 data show that even the addition of 70% lime and 15% ferric chloride, vacuum filter cake was only 21% solids. Suspended solids recoveries and filter yields were not very good.

Temperatures in the thermal reactor were increased to 200°C (400°F) in an attempt to improve the dewatering characteristics of heat treated waste activated sludge. Results for pressure filtration are contained in Table 5 and vacuum filtration results are summarized in Table 6. The undigested sludge produced a cake of 40 to 44% on the pressure filter with yields of 4.3 to 5.4 $kg/m^2/hr$ (0.9-1.1 $lb/ft^2/hr$). This compares well with earlier results(2). Vacuum filtration of the undigested sludge was also successful. Cakes of 33% were produced with filter yields of 12 $kg/m^2/hr$ (2.5 $lb/ft^2/hr$). Suspended solids recovery was marginal at 91%. No conditioning chemicals were needed.

Digestion of the heat treated sludge resulted in reduced dewatering properties. The filter press would not produce a reasonable cake unless large amounts of conditioning chemical were added. Even conditioning with 75% lime and 15% ferric chloride produced marginal results. Vacuum filtration results on the digested sludge were not much better. Although a cake of 24 to 29% TS as produced, its consistency and discharge were unacceptable. Filter yields and suspended solids recoveries were poor.

Pathogen Study --

A routine pathogen sampling program was not conducted during this phase of the study. However, two sets of samples were taken during the 200°C (400°F) heat treatment phase and analyzed for coliforms. Each sample set was composed of three discrete grab samples: influent to the thermal reactor, heatrate (or thermal reactor discharge) and effluent from the anaerobic digester. The two influent samples averaged 1.4×10^7 MPN/100 ml.

TABLE 6. VACUUM FILTRATION OF HEAT TREATED WAS (200 °C).

Filter Run #	Sludge Type	Filter Yield* kg/m²/hr (lb/ft²/hr)	Cycle Time min:sec	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Discharge
3	Thickened Heatrate	19.5 (3.99)	1:55	9.67	8.67	2.93	1.93	78	34.3	Poor
4	Thickened Heatrate	13.5 (2.77)	4:07	9.67	8.67	1.74	0.74	91.5	34.3	Fair
5	Thickened Heatrate	11.6 (2.37)	6:35	9.67	8.67	1.83	0.83	90.5	33.1	Good
6	Digested Heatrate	0.21 (0.044)	1:56	2.23	1.85	1.23	0.85	54	24.3	Very Poor
7	Digested Heatrate	0.18 (0.037)	4:00	2.23	1.85	0.72	0.34	82	27.2	Very Poor
8	Digested Heatrate	0.14 (0.028)	6:00	2.23	1.85	-	-	-	29.4	Very Poor

*Cloth Medium: KS-515

THERMAL REACTOR PARAMETERS

Temperature: 200°C (400 °F)
Pressure: 2758 kPa (400 psi)
Detention Time: 29 min
Air: 0.0 l/s (scfm)

DIGESTER PARAMETERS

Temperature 49°C (120°F)
Detention Time 28 days

The results from the heatrate and digester effluent samples in one case were inconclusive because the MPN values were less than anticipated and proper dilutions of the sludge sample were not made. The data could only be reported as less than 300 MPN/100 ml. The results from the second set of samples were very encouraging; heatrate at 23 MPN/100 ml and effluent at 3 MPN/100 ml. It should be noted that great care was taken in gathering these samples (e.g., the affected piping inside the trailer was steam cleaned prior to sampling). Based on limited data, the thermal treatment process was very effective in pasteurizing the WAS.

Heavy Metals --

Samples were not analyzed during this phase of the study for heavy metals. However, thickened waste activated sludge was analyzed during the next step of this study and heavy metal data are discussed later.

Modified LPO Conditioning of WAS

Pretreatment of thickened waste activated sludge under modified wet oxidation conditions was initiated on November 15, 1976. Because relatively low pressures and small amounts of air were used, low pressure oxidation (LPO) is used to describe modifications to the wet oxidation process. In addition to providing 0.6 l/s (1.2 scfm) of air, the thermal reactor temperature was increased to 220°C (425°F) for this phase. The reactor pressure and detention time remained at 2758 kPa (400 psi) and 29 min respectively. The temperature was increased above that previously maintained under heat treatment conditions to improve the dewatering properties of the sludge and to increase the degree of organic solubilization.

The thermal conditioning unit was operated under the above conditions until December 15, 1976 at which time it was taken out of service for a routine acid flushing. Various operational problems prevented continued operation until January 12, 1977. Two days later, problems with the gas recirculation system on the 45-m^3 (12,000-gal) pilot digester further delayed start-up and the entire stabilization system was not fully in service until January 24, 1977. This phase of the study continued until April 12, 1977.

Stabilization: Anaerobic Digestion --

Table 7 provides a summary of the thermal conditioning-anaerobic digestion stabilization system used during steady-state operation from February 28 to March 31, 1977. These data are valuable only as indicators of successful anaerobic digestion since the digester was not at equilibrium. During this period, the digester received an average of 2.1 m^3/day (548 gpd) of LPO conditioned sludge corresponding to a detention period of 21.9 days and a total volatile solids loading of 0.023 kg/m^3/day (0.05 lb/ft^3/day). The reported data are based on one complete hydraulic detention time. Under these conditions, volatile solids and COD were destroyed. Operation of the digester was stable during this period as evidenced by the pH, volatile acids, and alkalinity values. The toxicity problems encountered at Standford(1) were not evident in the pilot scale digester.

TABLE 7. DIGESTER RESPONSE TO LPO CONDITIONED WAS FROM FEB. 28 - MARCH 31, 1977

PERFORMANCE	Units	Total System	Digestion
VS Destruction	kg/day(lb/day)	19.2(42.3)	15.5(34.2)
VS Destruction	%	52.7	47.4
COD Removal	%	42.9	42.6
Gas Production	m^3/kg (ft^3/lb) VS destroyed	0.69(11.0)	0.85 (13.7)
Methane Production	m^3/kg (ft^3/lb) COD removed	0.37(5.9)	0.37 (6.0)
OPERATING PARAMETERS			
Digester Volume	m^3(gal)	--	45.4(12,000)
Average Feed Rate	m^3/day (GPD)	--	2.1(584)
Hydraulic Detention Time	days	--	21.9
VS Loading	kg/m^3/day(lb/ft^3/day)	0.81(0.05)	0.72(0.045)
Gas Production	m^3/day(ft^3/day)	13.2(467)	13.2(467)
Methane Content	%	66.2	66.2
Temperature	°C(°F)	--	49(120)

Constituents		Influent	Heatrate	Effluent
pH		6.66	6.10	7.74
Total Solids	%	3.07	2.24	1.50
Volatile Solids	%TS	72.5	70.3	55.2
Total Dissolved Solids	mg/l	2,420	3,550	3,210
Fixed Solids	kg/day(lb/day)	30.4*	30.2	30.6
Alkalinity	mg/l	1,270	1,250	4,660
Volatile Acids	mg/l	900	800	580
Chloride	mg/l	448	353	--
Total COD	mg/l	26,600*	26,500	15,200
Soluble COD	mg/l	1,320*	13,700	4,520
Coliforms	MPN/100 ml	4.9×10^8	1.5×10^3	43
Fecal Coliforms	MPN/100 ml	1.2×10^8	7.5×10^2	43
Salmonella sp.	MPN/100 ml	4.9×10^3	1	1
Total Kjeldahl Nitrogen	mg/l	2,210	1,820	1,860
Ammonia Nitrogen	mg/l	235	415	1,280

*Corrected for steam dilution

Thermal Reactor Parameters

Temperature: 220°C (425°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

The performance of the anaerobic digester was essentially the same under all three waste activated sludge thermal pretreatment shemes. Temperatures ranging from 170° to 200°C (340° to 400°F) without the addition of air and temperatures of 220°C (425°F) with the addition of air did not have any apparent effect on digester volatile solids destruction and gas production. Table 8 is a comparison of pertinent information regarding digester performance under the three conditions of thermal pretreatment.

Stabilization: Anaerobic Filtration --

Steady-state filter operation was not attained until the end of January 1977 and the data presented in Table 9 represents continuous operation from February 1 to March 22, 1977. Influent and effluent samples were collected daily and analyzed for pH. The remaining constituents were determined twice weekly with the exception of the nitrogen analysis which was performed on a weekly basis.

The filter used in this study was seeded with thermal conditioned digested sludge to develop an anaerobic culture prior to applying the thermal treatment liquors. The seeding operation consisted of filling a 3.8 m^3 (1,000 gal), insulated holding tank with digested sludge and continuously recycling the tank contents through the filter. Some operational problems were encountered during this period and were related to excessive heat loss through the filter. These problems were resolved by installing an auxiliary external heating coil around the filter to maintain a constant temperature of 52°C (125°F). Following approximately 5 days of recycling digested sludge, the 3.8 m^3 (1,000 gal) holding tank began to be fed with thermal treatment decant liquors and the mixture was intermittently fed to the filter at a rate of 1.0 m^3/day (275 gpd). No operational or toxicity problems were encountered during the transition from feeding digested sludge to applying thermal treatment liquors.

Table 9 summarizes average filter performance data during seven weeks of continuous operation. At an average hydraulic detention time of 2.2 days and a total COD loading of 5.8 kg/m^3/day (0.36 lb/ft^3/day) a net reduction of 38.8% of the applied COD was achieved. A daily gas quantity of 4.0 m^3 (140 ft^3) with an average methane content of 73.6% was recorded corresponding to a unit methane production of 0.55 m^3/kg COD destroyed (8.9 ft^3/lb). Theoretically, only 0.35 m^3/kg (5.6 ft^3/lb) of methane should have been produced. The cause of the high methane production value from the anaerobic filter is not known. Other studies have been conducted with a small scale anaerobic filter utilizing sludge that was thermally treated on a batch basis in a thermal bomb. In that study, the filter was operated at a detention time of 2 days and a COD loading of approximately 4.8 kg/m^3/day (0.30 lb/ft^3/day). Under these conditions, 76% of the COD was removed with a unit methane production of 0.35 m^3/kg (5.6 ft^3/lb). The reason(s) for the relatively low COD reduction encountered with the pilot filter as compared to the laboratory investigation(3) could be due to errors in COD measurement.

TABLE 8. COMPARISON OF PILOT SCALE DIGESTER PERFORMANCE UNDER VARIOUS CONDITIONS OF THERMAL PRETREATMENT.

PARAMETERS	Thickened Waste Activated Sludge			Primary/WAS Blend
	Heat Treatment 170-190°C(340-370°F)	Heat Treatment 200°C(400°F)	LPO Conditioning 220°C(425°F)	LPO Conditioning 200°C(400°F)
VS loading kg/m³/day (lb/ft³/day)	0.75 (0.047)	0.59 (0.037)	0.80 (0.05)	0.64 (0.04)
Hydraulic Detention Time days	27	28	22	22
VS Destruction	43%	43%	47%	41%
COD Removal	29%	37%	43%	44%
Soluble Effluent COD mg/l	3100	3900	4500	3800
Gas Production m³/kg VS destroyed (ft³/lb)	0.94 (15.0)	0.95 (15.2)	0.85 (13.7)	1.23 (19.8)
Methane Production m³/kg COD removed (ft³/lb)	0.60 (9.7)	0.41 (6.6)	0.37 (6.0)	0.39 (6.2)

TABLE 9. ANAEROBIC FILTER PERFORMANCE ON DECANT LIQUORS FROM LPO CONDITIONED WAS (220°C)

OPERATING PARAMETERS FOR ANAEROBIC FILTER			
Filter Volume	$m^3(ft^3)$	2.3(81)	
Feed Rate	m^3/day (GPD)	1.0(275)	
Detention Time	days	2.2	
COD Loading	kg/m^3/day (lb/ft^3/day)	5.8(0.36)	
COD Removal	%	38.8	
Gas Production	m^3/day (ft^3/day)	4.0(140)	
Gas Composition	$\%CH_4$	73.6	
Methane Production	m^3/kg (ft^3/lb) COD destroyed	0.6(8.9)	
Temperature	°C (°F)	52 (125)	
CONSTITUENTS		Influent	Effluent
pH		7.38	7.67
Volatile Acids	mg/l CH_3COOH	3135	940
Alkalinity	mg/l $CaCO_3$	3785	4520
COD	mg/l O	12,850	7860
BOD_5	mg/l O	--	2360
Soluble BOD_5	mg/l O	--	1990
Suspended Solids (SS)	mg/l	1260	980
Volatile SS	%	61.8	70.6
Total Dissolved Solids	mg/l	6600	4830
Total Kjeldahl Nitrogen	mg/l	1700	1730
Ammonia Nitrogen	mg/l N	1310	1490

The decant liquors produced from gravity thickening of LPO conditioned WAS are amenable to anaerobic filtration. The process proved to be very stable in its operation over a period of 20 hydraulic detention times. In terms of a thermal conditioning side-stream treatment device, the anaerobic filter demonstrated on the order of 40% removal of the applied COD at a detention time of two days.

Mechanical Dewatering --

Mechanical dewatering experiments were conducted on digested and undigested LPO conditioned waste activated sludge. Dewatering equipment used in these evaluations included a 0.24-m^2 (8.4-ft^2) pressure filter, 1-m (3 ft) diameter by 0.3-m (1-ft) vacuum filter, 1.2-m (48-in) diameter basket centrifuge and a 0.5 by 1.5-m (20 by 50-in) scroll centrifuge. Several dewatering experiments were conducted using gravity thickened digested sludge from a 0.56-m (22-inch) diameter by 1.8-m (6-ft) gravity thickener.

Pressure Filtration -- Filter press test runs were conducted to demonstrate the impact of anaerobic digestion on the dewatering characteristics of LPO conditioned WAS. Data are presented in Table 10. Two filter press runs were conducted to yield comparative data on the dewatering properties of undigested LPO conditioned sludge. Performance of the

TABLE 10. PRESSURE FILTRATION OF LPO CONDITIONED WAS (220°C)

Sludge Type	Run #	Filter Yield* $kg/m^2/hr$ ($lb/ft^2/hr$)	Press Time min	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Consistency/ Discharge
Thickened Heatrate	8	4.10 (0.84)	90	9.51	8.61	0.106	0.032	99.7	47.8	Good/ Fair
Thickened Heatrate	9	5.62 (1.15)	60	9.51	8.61	0.110	0.021	99.8	39.8	Good/ Fair
Digested Heatrate	10	--	90	1.23	0.83	0.6	0.169	79.7	-	Very Poor/ Very Poor

*Cloth Medium: 3-P

Thermal Reactor Parameters
Temperature: 220°C (425°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

Digester Parameters
Temperature: 49°C (120°F)
Detention Time: 27 days

undigested sludge (runs 8 and 9) was good. Cake solids of 47.8% TS with a filter yield of 4.1 $kg/m^2/hr$ (0.8 $lb/ft^2/hr$) were obtained at a 90-min press time. Pressures of 690 kPa (100 psi) were used. Shortening the cycle time to 60 min resulted in a higher filter yield, 5.6 $kg/m^2/hr$ (1.15 $lb/ft^2/hr$), but a wetter cake at 39.8% TS. The filter press cakes self-discharged from the fabric but some extra cleaning of the media was necessary. Pressure filtration of the digested conditioned sludge (run 10) was not successful. When the plates were disengaged, the captured solids were poorly formed and had to be manually scraped from the media. Due to the plastic quality of the retained solid, no cake samples were taken.

In order to achieve a better representation of pressure filtration performance on digested LPO conditioned WAS the sludge was thickened prior to filtration. The underflow solids concentration was 8% TS which is similar to the 9.5% total solids feed used in the undigested sludge pressure filtration tests. No data can be reported due to failure of the high pressure feed pump to deliver 690 kPa (100 psi) pressures to the filter. No conclusions can be made regarding the filtration properties of thickened-digested, LPO conditioned WAS.

Vacuum Filtration -- Vacuum filtration test runs were also conducted, in an effort to measure the changes in dewatering performance due to anaerobic digestion of the LPO conditioned WAS. In these tests, some digested conditioned sludge was gravity thickened prior to vacuum filtration. Several test runs of the unthickened-digested sludge were also made. Background test runs were conducted on gravity thickened-undigested sludge.

Results for vacuum filtration of undigested, LPO conditioned waste activated sludge are presented in Table 11. The results compare favorably with previous experiments(2). Cake solids of 35 to 38% were obtained with good operation and discharge of the cake solids. Filter yields ranged from 9.0 to 22.1 $kg/m^2/hr$ (1.8 to 4.5 $lb/ft^2/hr$). Suspended solids recoveries were relatively poor but this was the result of not having an adequate seal between the vacuum drum and the filtering media.

TABLE 11. VACUUM FILTRATION OF UNDIGESTED LPO CONDITIONED WAS (220°C)

Run #	Filter Yield[a] kg/m²/hr (lb/ft²/hr)	Cycle Time min:sec	Feed[b]		Filtrate		Recovery %	Cake %TS	Discharge
			%TS	%SS	%TS	%SS			
9	17.2 (3.53)	2:03	6.45	5.45	3.06	2.06	62.2	36.4	Good
10	9.9 (2.02)	4:37	6.45	5.45	1.55	0.55	89.9	37.6	Good
11	9.0 (1.85)	6:35	6.45	5.45	2.52	1.52	72.1	36.4	Good
12	22.1 (4.52)	2:02	10.5	9.4	-	-	-	36.1	Good
13	14.8 (3.04)	4:48	10.5	9.4	3.06	1.96	79.1	35.3	Good
14	12.4 (2.54)	6:45	10.5	9.4	3.02	0.92	90.2	34.8	Good

[a]Cloth Medium: KS-515

[b]Sludge Type: Thickened Heatrate

Thermal Reactor Parameters

Temperature: 220°C (425°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

Six attempts were made to filter unthickened LPO conditioned-digested WAS but in each case the sludge did not adhere to the belt and the runs were terminated. The unsuccessful filter operation was again attributed to the low solids content of the sludge. Nine vacuum filter runs were therefore preceded by gravity thickening of the LPO conditioned-digested waste activated sludge to improve filter performance and operation. These results are presented in Table 12, and were collected while prethickening with the addition of 5, 1.1, and 0 g/kg (10, 2.2 and 0 lb/ton) of cationic polymer respectively.

Gravity thickening of digested, LPO conditioned sludge with the addition of 5 g/kg (10 lb/ton) of polymer resulted in a thickened sludge of 9.5% suspended solids with 99% recovery in the thickener. Data in Table 12 show that vacuum filter performance was successful. Cake solids of 28 to 30% were obtained with filter yields of 8.8 to 15.1 kg/m^2/hr (1.8 to 3.1 lb/ft^2/hr). The cake discharge from the fabric was marginal. Prethickening using 1.1 g/kg (2.2 lb/ton) of polymer resulted in a thickened sludge of 7.8% suspended solids with 92% solids recovery in the thickener. Vacuum filtration performance was successful. Cake solids of 27 to 29% were obtained with yields of 10.2 to 21.5 kg/m^2/hr (2 to 4.4 lb/ft^2/hr).

With no polymer addition to the thickener, the underflow solids were 5.8% but the solids recovery dropped to 55%. Vacuum filtration was suc-

TABLE 12. VACUUM FILTRATION OF DIGESTED LPO CONDITIONED WAS * (220°C).

Gravity Thickener Polymer Dose g/kg(lb/ton)	Run #	Filter Yield** $kg/m^2/hr$ ($lb/ft^2/hr$)	Cycle Time min:sec	Feed		Filtrate		Recovery %	Cake %	Discharge
				%TS	%SS	%TS	%SS			
5(10)	11	15.1 (3.1)	2:05	9.92	9.52	0.52	0.12	98.8	27.6	Poor
5(10)	12	10.3 (2.1)	4:45	9.92	9.52	0.55	0.15	98.4	28.6	Fair
5(10)	13	8.8 (1.8)	6:45	9.92	9.52	0.45	0.05	99.4	29.6	Fair
1.1 (2.2)	14	21.5(4.41)	1:55	8.22	7.85	1.30	0.93	88.1	26.6	Fair-Good
1.1 (2.2)	15	13.3(2.73)	4:09	8.22	7.85	0.73	0.36	95.4	27.5	Fair-Good
1.1 (2.2)	16	10.2(2.08)	6:25	8.22	7.85	0.58	0.21	97.6	28.8	Fair-Good
0	17	9.0(1.84)	2:00	6.14	5.77	1.72	1.35	76.6	31.7	Good
0	18	7.2(1.48)	4:05	6.14	5.77	1.37	1.00	82.6	31.4	Good
0	19	5.6(1.14)	6:35	6.14	5.77	0.84	0.47	91.8	30.7	Fair

* Thermal Reactor Parameters

Temperature: 220°C (425°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

Digester Parameters

Temperature: 49°C (120°F)
Detention Time: 21.9 days

** Cloth Medium: KS-515

successful. The cakes were slightly drier than in the polymer conditioned runs, but the vacuum filter yields and suspended solids recoveries were not as good.

The conclusion from this work is that prethickening of the digested, LPO conditioned WAS greatly improves filtration characteristics. A polymer dose of 1 to 1.5 g/kg (2 to 3 lb/ton) is adequate for good gravity thickening performance. The digestion of LPO conditioned waste activated sludge results in a decrease of 6 to 9% TS in vacuum filtration cake solids.

Basket Centrifugation -- A 1.2-m (48-in) diameter basket centrifuge was used to dewater digested LPO conditioned waste activated sludge. Digested primary sludge from the JWPCP was blended with digested LPO conditioned WAS and the mixture was dewatered in the same basket centrifuge. No basket centrifuge dewatering tests were conducted on the undigested LPO conditioned WAS.

Basket centrifuge dewatering data are presented in Table 13. All test runs were conducted at a sludge feed rate of 3.2 l/s (50 gpm); the basket was operated at 1400 rpm producing 1350 g's at the bowl wall. Cationic polymers were used as a conditioning agent.

Results for the LPO conditioned WAS test runs are shown in Table 13 as Runs 1, 2, and 3. A polymer dosage of 1.6 g/kg (3.2 lb/ton) was adequate to produce 23% cake and a centrate quality of 1200 mg/l SS. Increasing the polymer dose to 2.3 g/kg (4.5 lb/ton) did not significantly improve performance; cake solids increased to 25% and centrate quality improved to 700 mg/l SS. No cake samples were taken because the test runs were aborted when the supply of feed sludge was exhausted.

The results for Runs 5, 6, and 7 show the dewatering performance of the digested primary-digested LPO conditioned WAS blend. The dewatering performance of the blend was very similar to that of the LPO conditioned WAS. The difference was that a polymer dose of 1.1 g/kg (2.2 lb/ton) produced good results on the blend. Not enough data is available to firmly state that the addition of digested primary sludge results in a savings in polymer. Contrary to such a conclusion is the data presented for Run 4 that indicates 100% digested primary sludge, conditioned with 2.2 g/kg (4.3 lb/ton) of polymer, will dewater on a basket centrifuge to 23% cake solids and a centrate of 900 mg/l SS.

Scroll Centrifugation -- A low-speed 50-cm (20-in) diameter scroll centrifuge was installed and began operation in April 1977. Several runs were made on digested LPO conditioned waste activated sludge. The data are presented in Table 14. No tests were conducted on undigested LPO conditioned WAS. The hydraulic capacity of this centrifuge is on the order of 6.3 l/s (100 gpm). In the pilot scale thermal pretreatment-anaerobic digestion study only 2.3 m^3 (600 gal) per day of digested sludge was processed. In order to carry out dewatering studies, it was necessary to

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TABLE 13. BASKET CENTRIFUGATION OF DIGESTED PRIMARY AND LPO CONDITIONED WAS.

Basket Run #	Bowl Speed rpm	Bowl Accel. g's	FEED l/s (gpm)	FEED % Dig. LPO WAS	FEED % Dig. Primary	FEED % TS	Cycle Time min:sec	Centrate %SS	Recovery %	Cake* %TS	Polymer Type	Polymer g/kg (lb/ton)	Mass Balance Error %
1	1400	1350	3.2 (50)	100	0	1.20	70:00	0.12	87.4	23.0	728	1.6 (3.2)	6.5
2	1400	1350	3.2 (50)	100	0	1.20	10:00	0.34	64.2	-	-	0.0	-
3	1400	1350	3.2 (50)	100	0	1.67	41:40	0.07	94.6	24.9	2535	2.3 (4.5)	7.8
4	1400	1350	3.2 (50)	0	100	3.01	22:05	0.09	96.5	23.0	728	2.2 (4.3)	7.6
5	1400	1350	3.2 (50)	21	79	2.35	29:44	0.09	95.5	22.6	728	1.1 (2.2)	1.4
6	1400	1350	3.2 (50)	21	79	2.35	10:00	0.44	78.4	-	-	0.0	-
7	1400	1350	3.2 (50)	23	77	2.31	32:00	0.11	94.5	22.2	728	2.2 (4.3)	9.9

*Excluding ~ 0.06 m^3 (2.2 ft^3) of skimmings.

Thermal Reactor Parameters

Temperature: 220°C (425°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

TABLE 14. SCROLL CENTRIFUGATION (KRUGER, 50 CM DIAMETER) OF DIGESTED LPO CONDITIONED WAS

Run #	Flow l/s (gpm)	Polymer Dose g/kg (lb/ton)	Feed Solids %TS	Centrate SS mg/l	Cake Solids %TS	Recovery %	Relative Scroll Speed, rpm
1	3.8(60)	0	1.6	9100	24	24	30
2	3.8(60)	4.2(8.4)	1.6	1800	18.6	85	30
3	3.8(60)	5.6(11.2)	1.6	1900	19.1	84	30
4	3.8(60)	4.2(8.4)	1.6	1600	21.8	87	20
5	3.8(60)	5.6(11.2)	1.6	2000	21.0	83	20
6	3.8(60)	0	1.4	7400	17.3	27	16
7	3.8(60)	3.3(6.6)	1.4	2900	17.5	71	16
8	3.8(60)	5.0(9.9)	1.4	2300	17.6	77	16
9	3.8(60)	5.6(11.2)	1.6	1800	3	85	16
10	3.8(60)	13.0(26.0)	1.4	2900	21.3	71	16
11	5.0(80)	*	*	*	*	*	*

*No Data, Excessive Centrate Foam

Bowl Speed: 1958 rpm (1100 g's)
Pool Depth: 10.7 cm (4.2 in)

store digested sludge for as long as one week prior to the actual dewatering. The effect of this storage on the dewatering properties of the sludge are unknown. Because of the short time available, it was not possible to determine whether the centrifuge parameters used in the test work were optimal. However, Table 14 data do indicate relative dewatering characteristics of the digested LPO conditioned WAS.

During all test runs the bowl was operated at 1958 rpm, producing a force of 1100 g's at the wall of the bowl. The pool depth was set at maximum and relative scroll speeds were 16 to 30 rpm. Initial test runs at 5 l/s (80 gpm) resulted in tremendous foaming problems; the foam was so severe that it built up inside the machine and was forced out through the solids discharge hopper. The sludge feed rate had to be dropped back to 3.8 l/s (60 gpm) for successful operation. Even at 3.8 l/s (60 gpm), the centrate contained enough foam to cause problems in a full-scale installation. Cationic polymer doses ranged from 0 to 5.6 g/kg (0 to 11.2 lb/ton).

Under the range of test conditions, Table 14 shows that cake solids of 17 to 24% could be obtained with centrate concentration of more than 1500 mg/l SS with polymer doses of 3.3 to 13.0 g/kg (6.6 to 26 lb/ton). Based on qualitative observation of the sludge cake, a total solids value of 21% or greater is necessary to insure adequate conveying properties.

Gravity Thickening -- Gravity thickening studies were conducted on both a batch basis and on a continuous flow basis. Comparative tests were conducted on digested and undigested LPO conditioned waste activated sludge as well as tests on digested non-thermally conditioned WAS. The gravity thickener was 0.56 m (22 in) in diameter and 1.8 m (72 in) high. For the

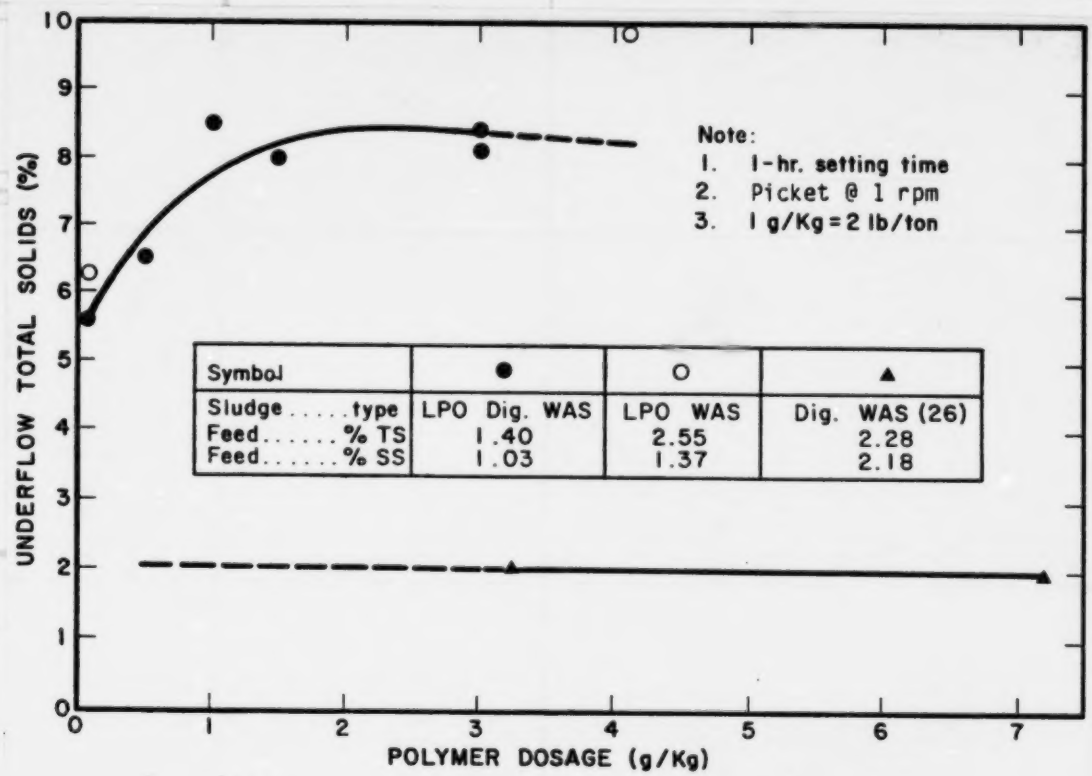


Figure 5. Gravity thickener underflow solids versus polymer dosage for heat treated WAS.

continuous flow tests, an overflow was placed 0.33 m (13 in) below the top of the reactor which reduced the usable volume to 036 m^3 (96 gal). The thickener was equipped with 0.61 m (24 in) long vertical picketts rotating at 1 rpm on the bottom of the tank. Cationic polymers were used to condition various sludges.

The results of the batch settling tests are presented in Figures 5 and 6. Three sludge types were used: undigested LPO conditioned WAS, digested LPO conditioned WAS and digested non-thermally treated WAS from another LACSD's treatment plant (District 26 WRP). Figure 5 shows how the underflow solids increased with the addition of polymer; Figure 6 shows solids recovery. District 26 WRP digested sludge did not separate even with a polymer dosage of 7.3 g/kg (14.5 lb/ton); underflow solids were only 2%, and 90% of the applied solids escaped in the overflow. The digested LPO conditioned sludge required roughly 1.5 g/kg (3 lb/ton) of polymer to produce and 8% solids concentration in the underflow and greater than 90% suspended solids recovery. The undigested LPO conditioned sludge appeared to show the best gravity separation characteristics. However, only two tests were conducted: one with no polymer and one with 4 g/kg (8 lb/ton)

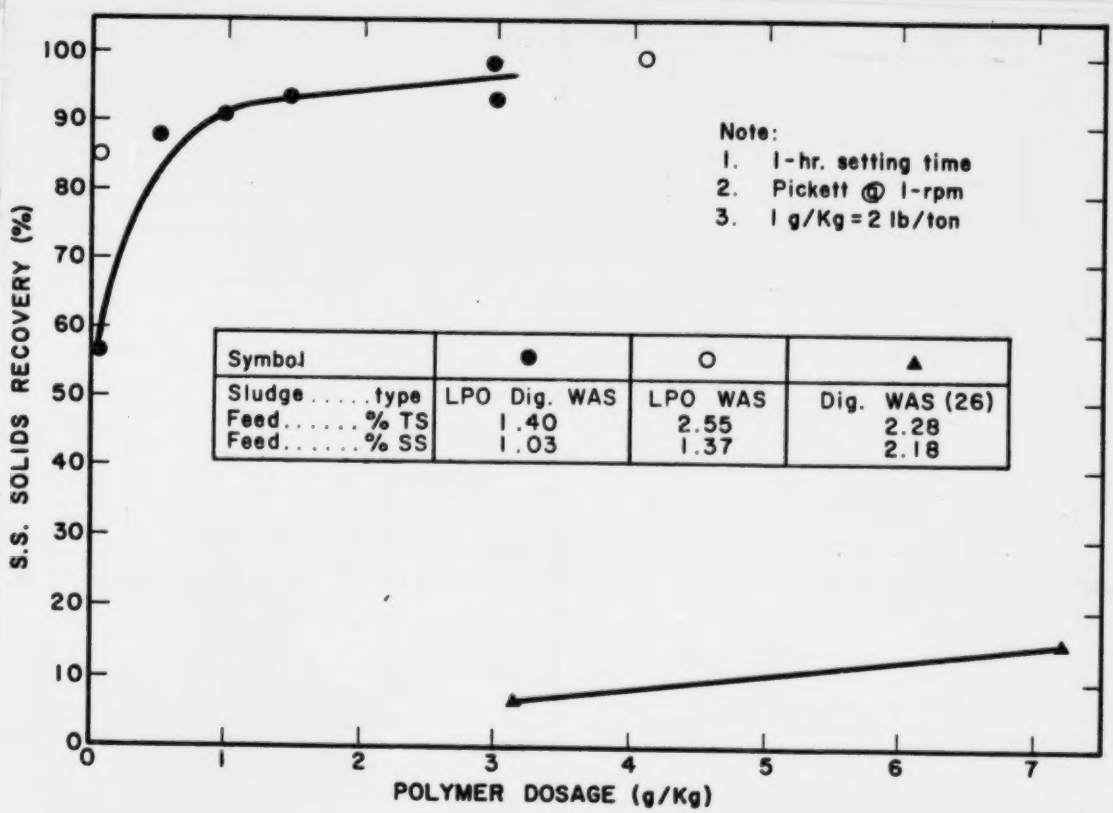


Figure 6. Gravity thickener overflow suspended solids versus polymer dosage for heat treated WAS.

of polymer. The results from these tests were better than comparable test results for the digested LPO conditioned sludge.

Because of these encouraging results, another series of more rigorous tests were conducted. Digested, LPO conditioned WAS was dosed with 1.4 g/kg (2.7 lb/ton) of cationic polymer and introduced into a 15 cm (6 in) diameter by 25.4 cm (10 ft) lucite column. Vertical pickets inside the column were again rotated at 1 rpm. The decrease in height of the solids interface was noted over a 2-hr period. The underflow solids were then mixed with fresh polymer conditioned digested sludge and the same settling test was conducted at this higher initial solids content. A plot of the solids interface height with time for initial solids concentration of 1.3 to 7.3% is shown in Figure 7. The slope of each of these curves expresses a settling velocity. When settling velocity is plotted against initial solids concentration (semi-log plot), a straight line can be constructed and is shown in Figure 8.

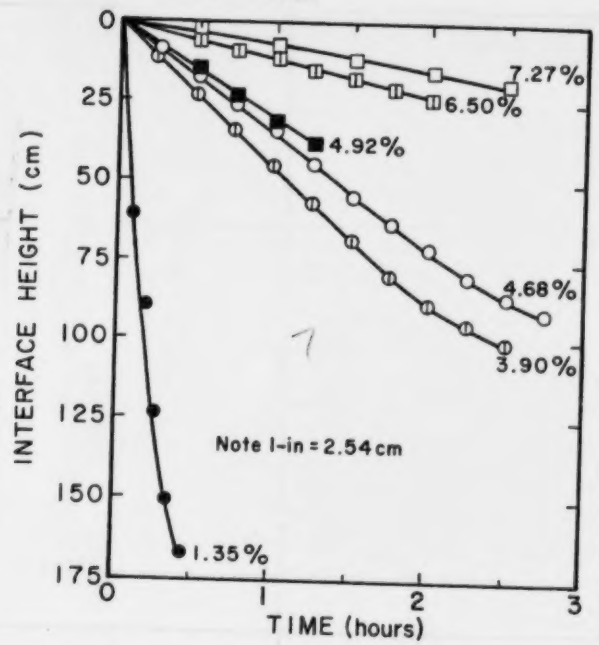


Figure 7. Gravity thickener interface height versus time for heat treated WAS.

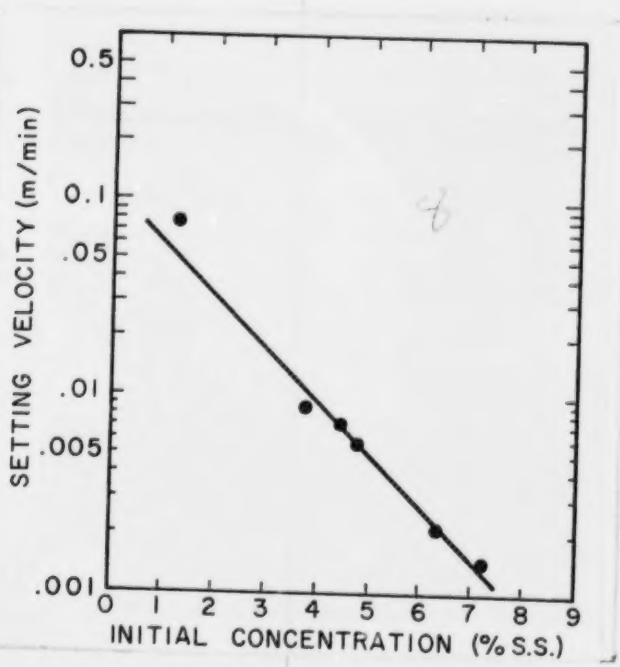


Figure 8. Gravity thickener settling velocity versus intial SS concentration for heat treated WAS.

Using the straight line plot in Figure 8, it is possible to predict the size of a full-scale gravity thickener. If an initial solids concentration and a desired underflow concentration are specified, solving an equation developed by Coe and Clevenger(4) will yield the surface area requirements for a gravity thickener. Such an analysis was made for a 4.4 m^3/s (100 mgd) pure oxygen activated sludge system employing LPO conditioning followed by anaerobic digestion. The diameter of a gravity thickener required to concentrate a 1.3% TS LPO conditioned WAS digested sludge to an underflow solids of 10% TS was determined to be 8.5 m (28 ft).

In order to verify these results, the 0.56 by 1.5-m (22 by 59-in) gravity thickener was operated on a continuous basis. A flowrate was determined to achieve the solids loading rate predicted by the Coe-Clevenger equation. The sludge was conditioned with 1.4 g/kg (2.7 lb/ton) of cationic polymer. A 0.4 m (15 in) sludge blanket was built up in the thickener and underflow solids were removed periodically to maintain this level. This test was allowed to run continuously for several hours. At the conclusion of the test, an overflow sample was taken and analyzed for suspended solids and an underflow sample was analyzed for total solids. A comparison of the predicted performance and the actual performance is presented in Table 15. The results for Run 3 closely match those predicted by solution of the Coe-Clevenger equation. The underflow total solids were 9.94% with an overflow suspended solids of 940 mg/l. Run 1 and 2 also produced a concentrated underflow but the solids loading rates were only 70% of the desired value.

TABLE 15. VERIFICATION OF THE COE-CLEVENGER THICKENING MODEL USING LPO CONDITIONED WAS

Variables	Coe-Clevenger Model	Run 1 4/7/77	Run 2 4/12/77	Run 3 4/28/77
Feed Solids, % SS	1.3	0.92	0.92	0.92
Underflow, % TS	10.0	9.95	13.8	9.94
Solids Loading, $kg/m^2/hr$ ($lb/ft^2/hr$)	19.5(4.0)	9.3(1.9)	9.3(1.9)	19.6(4.0)
Surface Loading, $m^3/day/m^2$ (GPD/ft^2)	36 (885)	24(585)	24(585)	50(1250)
Hydraulic Detention Time, hr	--	1.5	1.5	0.7
Polymer Dose, g/kg(lb/ton)	1.4(2.7)	1.4(2.7)	1.4(2.7)	1.4(2.7)
SS Overflow, mg/l	--	1030	760	940
SS Recovery, %	--	88.8	91.7	89.8
Duration of Test Run, hr	--	5	10	--

Pathogen Study --

From the period of January 20 through April 13, 1977, seven sets of grab samples were taken and analyzed for coliforms, salmonellae and parasite eggs (Ascaris ova). The results are contained in Table 16. A detailed summary of this study is presented in the Appendix. Each sample set contained influent, heatrate (effluent from thermal reactor) and digester effluent samples. Six samples were also taken from a second digester treating non-thermal conditioned waste activated sludge; these represent control or baseline values.

Unlike earlier bacterial samples, it was not possible to steam-clean the sample lines inside the thermal reactor. High levels of bacteria in some of the heatrate samples probably represent poor sampling locations and poor sampling techniques. The effluent samples, with two exceptions, 3/2 and 3/17, are probably representative. It can be inferred from the data presented that the thermal pretreatment-anaerobic digestion scheme provides good pathogen kills but regrowth of coliforms may occur. Also, the data clearly show that in all cases anaerobic digestion without thermal pretreatment was much less effective in pathogen removal.

Odors --

A number of odor samples were taken during this phase of the study. The procedure involved placing a 0.03 m^3 (1 ft^3) box over a fresh sample and using a small pump to circulate air over the sample and out of the box through a discharge orifice. Samples were collected from the orifice and sent to an odor panel for analysis. The odor panel results are summarized in Table 17. Both the odor dilution ratio (Z) and odor strength, as judged by the odor panel, are reported.

In general, odor measurements are very hard to duplicate and usually require a large number of samples to adequately develop a reliable odor unit value. Not enough samples were taken on the thermal conditioning system to assign firm values. The data do indicate that the digested LPO conditioned sludge cake has about the same odor intensity as digested JWPCP primary sludge cake. It should be noted that the characteristic thermal conditioned odor has a different quality than does digested sludge. When dewatering experiments were being conducted in the JWPCP basket centrifuge building, the operators easily isolated the source of an unfamiliar odor even though only one centrifuge was dewatering LPO conditioned sludge while 20 or more centrifuges were operating on digested primary sludge. Data in Table 17 suggest that anaerobic digestion tends to reduce thermal conditioning odors. But the intensity and quality of the remaining odors was significant.

Heavy Metals --

Two liter grab samples were taken March 1, 1977 and analyzed for the following metals: arsenic, cadmium, copper, lead, mercury, nickel, silver, and zinc. The data are presented in Table 18. Total metal concentrations are expressed on a dry weight basis and soluble metal concentrations as mg/l. Total metal concentrations show an apparent increase following thermal conditioning. This results from destruction of volatile solids and thus a lowering of the weight of dry material in the heatrate and effluent

TABLE 16. SUMMARY OF MICROORGANISM DATA FOR LPO CONDITIONED WAS

Date 1977	Sample	Indicator Bacteria MPN/100 ml				Ascaris OVA/100ml	
		Total Coliform	Fecal Coliform	Fecal Strep.	Salmonellae	Total	Viable
1-20	Influent	2.3×10^{8}	4.3×10^{7}	ND	4×10^{3}	65	39
	Heatrate	1.5×10^{3}	7.5×10^{2}	ND	<1	7	1
	Effluent	43	43	ND	<1	< 0.3	< 0.3
2-02	Influent	7.5×10^{8}	2.0×10^{8}	ND	9.3×10^{4}	11	7
	Heatrate	2.1×10^{7}	6.4×10^{6}	ND	<1	13	< 2
	Effluent	43	43	ND	<1	6	< 6
	Control*	2.9×10^{7}	6.4×10^{6}	ND	2.3×10^{2}	5	5
2-17	Influent	4.3×10^{8}	4.3×10^{7}	ND	3.9×10^{3}	66	66
	Heatrate	2.3×10^{6}	1.5×10^{5}	ND	<1	< 2	< 2
	Effluent	7.5×10^{3}	3.9×10^{3}	ND	<1	10	< 1
	Control*	2.3×10^{7}	9.3×10^{6}	ND	4.3×10^{2}	25	8
3-02	Influent	2.3×10^{8}	2.3×10^{7}	ND	2×10^{3}	9	5
	Heatrate	1.5×10^{7}	4.3×10^{4}	ND	<1	2	< 1
	Effluent	2.3×10^{6}	9.3×10^{5}	ND	4.3×10^{2}	3	< 1
	Control*	4.3×10^{6}	4.3×10^{6}	ND	2.0×10^{2}	19	5
3-17	Influent	4.3×10^{8}	9.3×10^{7}	ND	1.1×10^{3}	9	< 5
	Heatrate	2.3×10^{2}	9	ND	<1	3	< 0.8
	Effluent	3.3×10^{4}	2.3×10^{4}	ND	2.3×10^{2}	2	2
	Control*	9.3×10^{7}	3.3×10^{6}	ND	2.8×10^{1}	28	14
3-30	Influent	2.0×10^{8}	4.3×10^{7}	ND	2.3×10^{5}	10	7
	Heatrate	<3	<3	ND	<3	3	< 2
	Effluent	9	4	ND	<1	1	< 0.7
	Control*	4.3×10^{6}	9.3×10^{5}	ND	1.4×10^{2}	3	3
4-13	Influent	9.3×10^{8}	2.3×10^{7}	ND	2.1×10^{3}	32	32
	Heatrate	4.6×10^{5}	4.3×10^{4}	ND	4	1	<0.5
	Effluent	43	<3	ND	<1	0.5	<0.5
	Control*	2.4×10^{8}	4.6×10^{7}	ND	4	12	12
Geometric Mean							
	Influent	3.9×10^{8}	5.0×10^{7}	ND	7.7×10^{3}	20	14
	Heatrate	4.5×10^{4}	4.5×10^{3}	ND	1	3	1.4
	Effluent	6.8×10^{2}	3.8×10^{2}	ND	6	1.7	1.0
	Control*	2.6×10^{7}	5.7×10^{6}	ND	43	12	7

* Control is anaerobic digested WAS without thermal pretreatment.

TABLE 17. SUMMARY OF ODOR RESULTS FOR LPO CONDITIONED WAS

Sample	Qualitative Observations	Odor Dilution* Ratio (Z)	Number of Samples
Effluent Air From Cake Samples			
Digested Primary	Strong Odor	9-1200	3
1 week Compost	Moderate Odor	50	3
Finished Compost	Slight Odor	6	2
LPO Conditioned, Digested WAS	Strong Odor	12-1500	2
Effluent Air From Liquid Samples			
Thickened WAS	Moderate Odor	40	2
Digested WAS	Moderate Odor	40	1
LPO Conditioned WAS	Strong Odor	720-3200	3
LPO Conditioned, Digested WAS	Strong Odor	40-1150	3
Anaerobic Filter Effluent	Strong Odor	1000	1

*The odor dilution ratio (Z) is the sum of the volume of odorous air and clean air required to reduce odor to the detection threshold divided by the volume of odorous air. See ASTM D 1391-78.

TABLE 18. SUMMARY OF HEAVY METALS DATA FOR UNDIGESTED LPO CONDITIONED WAS

Constitutent		INFLUENT Total mg/kg	INFLUENT Soluble mg/l	HEATRATE Total mg/kg	HEATRATE Soluble mg/l	EFFLUENT Total mg/kg	EFFLUENT Soluble mg/l
Arsenic	As	34.5	<0.01	39.6	0.08	58.9	0.06
Cadminum	Cd	44.8	0.006	59.3	0.003	58.9	0.002
Copper	Cu	760	0.06	850	0.03	980	0.02
Lead	Pb	690	0.02	720	0.05	1080	0.06
Mercury	Hg	5.69	0.0003	6.97	0.0003	8.58	0.0003
Nickel	Ni	220	0.04	210	0.70	690	0.50
Silver	Ag	48.3	0.006	50.8	0.004	78.6	0.001
Zinc	Zn	2100	0.20	3100	0.12	1800	0.07
Total Solids	mg/l	29,000	--	23,260	--	10,180	--

samples. The concentration of soluble arsenic and nickel were noticeably increased following thermal conditioning. The other metals did not show the same increase in soluble concentration.

Composting --

On March 10, 1977, a laboratory scale experiment was initiated to determine if digested LPO conditioned waste activated sludge would successfully compost. This study was conducted at a constant temperature of 53°C (127°F) and incorporated the use of a thermophilic temperature bath. Four 1-liter (0.25-gal) steel cyclinders were fabricated and placed in the bath. One cylinder was loaded with JWPCP compost product and water added to raise the initial moisture content to 42%. The second cylinder was charged with a blend of compost product and dewatered digested primary sludge. The initial moisture content of this blend approximated 50%. The third and fourth cylinders were charged with blends of compost product and dewatered digested LPO conditioned waste activated sludge. The initial moisture content of these blends were 64% and 56% respectively.

Each of the cylinders were taken out of the bath every other day and the contents mixed to maintain aerobic conditions and to allow moisture to escape. Figure 9 plots volatile solids as a function of time. Decomposition of organic matter was observed for each of the piles as evident by the decrease in volatile solids, and the preliminary indications are that thermally treated digested waste activated sludge may compost. It must be realized that ideal conditions were maintained during this investigation. The laboratory scale operation was conducted at a constant temperature and it is unknown at this time if thermophilic temperatures will be reached in full-scale operation. Another major concern regarding composting of thermal treated sludge is the potential for odor generation. The characteristic thermal treatment odors were detectable during the first two days of composting after which time each of the composting materials had a normal "earthy" odor.

PHASE II

Pretreatment of a blend of 65% raw primary sludge solids and 35% thickened waste activated sludge solids was initiated April 22, 1977. This blend was used because it approximates the blend that will exist in the Los Angeles/Orange County metropolitan service area, once all treatment plant have full secondary treatment. The primary sludge was obtained from the Joint Water Pollution Control Plant. Thickened waste activated sludge was either obtained from a 0.02 m^3/s (0.5 mgd) pure oxygen pilot plant at the JWPCP or was delivered from the LACSD's District 26 WRP.

The thermal reactor temperature was reduced to 200°C (400°F) and the pressure, hydraulic detention time, and air addition remained unchanged at 2758 kPa (400 psi), 29 min and 0.6 l/s (1.2 scfm) respectively. As explained earlier, these conditions have been described as modified low pressure oxidation (LPO). These thermal reactor conditions were not changed for the duration of the study, through September 20, 1977.

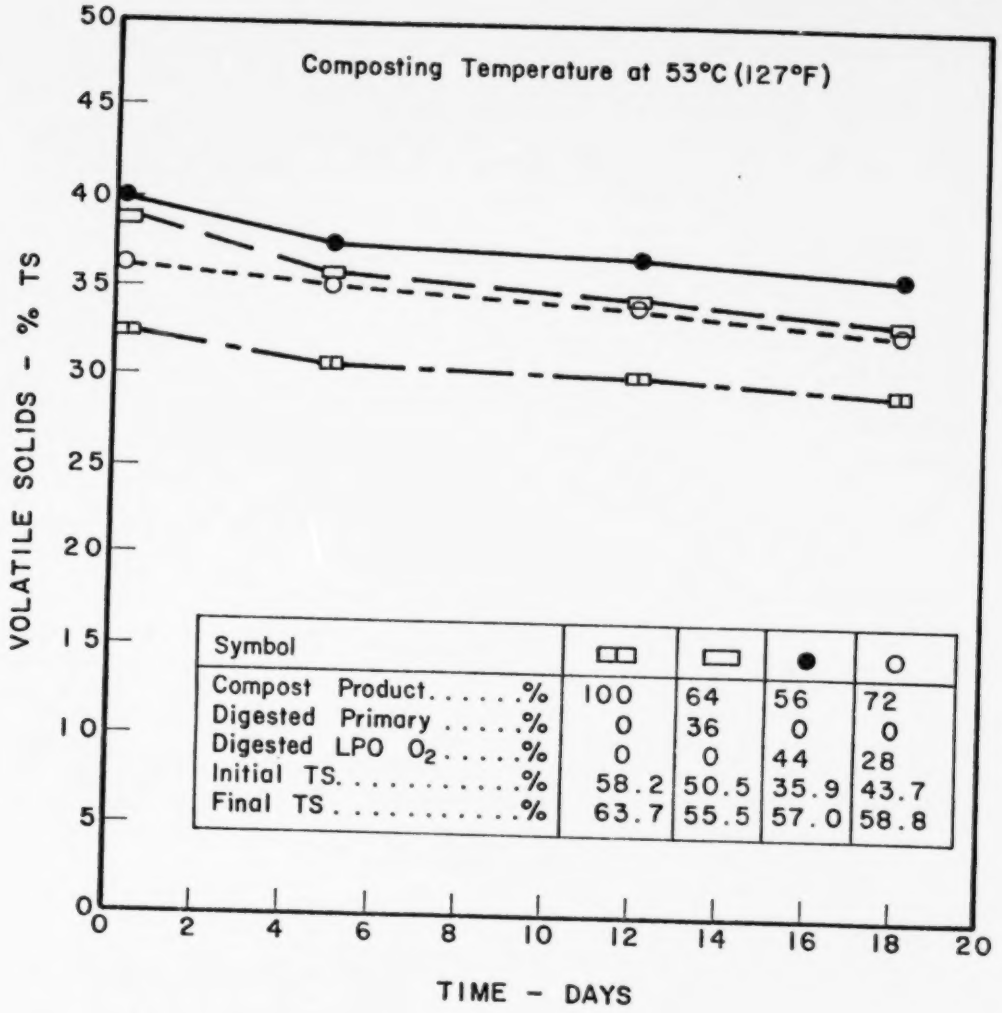


Figure 9. Laboratory composting study of LPO conditioned WAS.

Stablilization: Anaerobic Digestion

Figure 10 is a plot of digester performance during this phase of the thermal pretreatment study. For the period May 25 to July 31, 1977, steady-state conditions prevailed and by May 25 nearly two digester detention times had elapsed since the change in feed sludge. Table 19 summarizes the thermal conditioning-anaerobic digestion stabilization system during this period. The digester received an average flow of 2.04 m^3/day (540 gpd) of LPO conditioned blend corresponding to a hydraulic detention

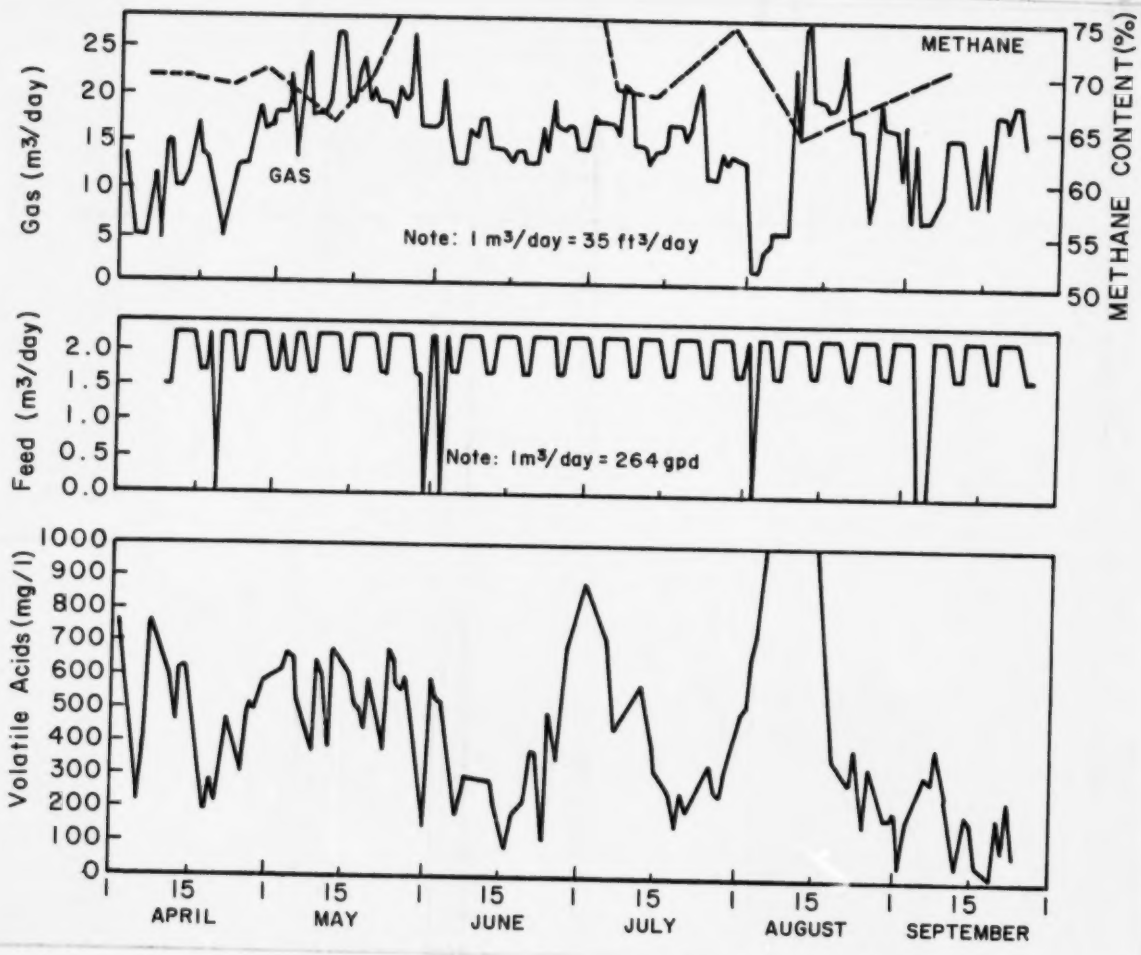


Figure 10. Digester response to LPO conditioned primary and WAS blend.

TABLE 19. DIGESTER RESPONSE TO LPO CONDITIONED PRIMARY AND WAS BLEND (MAY 26 - JULY 31, 1977).

PERFORMANCE	Units	Total System	Digestion
VS Destruction	kg/day(lb/day)	19.1 (42.0)	12.5 (27.5)
VS Destruction	%	51.9	41.4
COD Removal	%	42.0	43.9
Gas Production	m^3/kg (ft^3/lb) VS destroyed	0.81 (13.0)	1.23 (19.8)
Methane Production	m^3/kg (ft^3/lb) COD removed	0.42 (6.7)	0.39 (6.2)
OPERATING PARAMETERS			
Digester Volume	m^3(gal)	--	45.4 (12,000)
Average Feed Rate	m^3/day (GPD)	--	(540)
Hydraulic Detention Time	days	--	22.2
VS Loading	kg/m^3/day(lb/ft^3/day)	0.80(0.05)	0.64 (0.04)
Gas Production	m^3/day(ft^3/day)	15.4 (545)	15.4 (545)
Methane Content	%	70.2	70.2
Temperature	°C(°F)	--	48 (118)

Constituents		Influent	Heatrate	Effluent
pH		5.87	5.46	7.39
Total Solids	%	3.08	2.13	1.55
Volatile Solids	%TS	70.7	69.4	55.9
Total Dissolved Solids	mg/l	3,260	7,870	3,290
Fixed Solids	kg/day(lb/day)	15.2(33.5)*	13.3(29.4)	14.0(30.8)
Alkalinity	mg/l	1,870	1,480	3,970
Volatile Acids	mg/l	2,400	2,180	380
Chloride	mg/l	350	289	--
Total COD	mg/l	30,000*	31,000	17,400
Soluble COD	mg/l	4,000*	12,100	3,840

*Corrected for steam dilution

Thermal Reactor Parameters

Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

time of 22.2 days. The volatile solids loading for this period was 0.64 kg/m^3/day (0.04 lb/ft^3/day) and the average digester temperature was 48°C (118°F). Under these conditions, the digester destroyed 41% of the applied volatile solids and produced an average of 15.4 m^3/day (545 ft^3/day) of gas. The unit gas production was 1.2 m^3/kg (19.8 ft^3/lb) of volatile solids destroyed. Total COD removal was 44% to an effluent concentration of 17,400 mg/l; soluble effluent COD was 3,840 mg/l. Unit methane production per kg of COD removed was calculated to be 0.39 m^3/kg (6.2 ft^3/lb). Digester operation was stable as seen by the effluent pH, volatile acids and alkalinity values. No toxicity problems were encountered in this

digester. It is not apparent why the volatile solids destruction for the conditioned blend are so low. Under normal operation at the JWPCP, raw primary sludge undergoes nearly 50% volatile solids destruction during a 15-day mesophilic digestion. Stanford laboratory studies(1) concluded that there was no benefit in thermal conditioning primary sludge before digestion.

Using the chloride data for the influent and heatrate values, there was a 17.4% dilution effect due to the steam added to the thermal reactor. Taking into account the dilution effect, the LPO conditioning process destroyed 18% of the volatile solids in the feed sludge. This value is twice as great as when 100% waste activated sludge was LPO conditioned. The large amount of volatile solids destroyed in the thermal reactor may account for the lower percentage of volatile solids destruction in the subsequent anaerobic digestion process.

Stabilization: Anaerobic Filtration

The anaerobic filter reached steady state operation in early June 1977 but problems with the gas metering equipment were not corrected until July. Table 20 summarizes the performance of the anaerobic filter for the period July 10 to September 30, 1977. This period corresponds to nearly 20 hydraulic detention times for the reactor. An average of 0.55 m^3/day (145 gpd) of decant liquors from gravity thickened, LPO conditioned blend was fed to the filter; this corresponds to a 4.2 day hydraulic detention time and a COD loading of 2.72 kg/m^3/day (0.17 lb/ft^3/day). The temperature of the reactor averaged 52°C (126°F).

In July, a lithium tracer study was conducted on the anaerobic filter. A known amount of lithium chloride was dissolved in a liter of tap water. This solution was fed into the anaerobic filter and regular feeding was resumed. Samples were taken every two hours along the depth of the filter and analyzed for lithium. Within two hours, the lithium concentration was constant from all six sampling taps. This indicated that the anaerobic filter as operated during these studies was a completely mixed reactor and not the plug flow that was desired. It is not known why the anaerobic filter exhibited complete mix characteristics, or what effect this might have on COD removals.

The data in Table 20 show that the anaerobic filter was effective in removing 41% of the applied COD to an effluent concentration of 6700 mg/l SS. An average of 1.3 m^3 (46 ft^3) of gas was produced each day corresponding to a unit methane production value of 0.35 m^3/kg (5.6 ft^3/lb) COD removed. The operation of the filter and the daily gas production was very stable over the study period and there were no indications of toxicity.

As found in the earlier phase of this study, the decant liquors from a thermal conditioning unit are amenable to anaerobic filtration and approximately 40% COD removal can be expected.

TABLE 20. ANAEROBIC FILTER PERFORMANCE ON DECANT LIQUOR FROM LPO CONDITIONED PRIMARY AND WAS BLEND

OPERATING PARAMETERS FOR ANAEROBIC FILTER			
Filter Volume	m^3 (ft^3)	2.3 (81)	
Feed Rate	m^3/day (GPD)	0.5 (145)	
Detention Time	days	4.2	
COD Loading	kg/m^3/day (lb/ft^3/day)	2.7(0.17)	
COD Removal	%	41.2	
Gas Production	m^3/day (ft^3/day)	1.3 (46)	
Gas Composition	%CH_4	70*	
Methane Production	m^3/kg (ft^3/lb) COD destroyed	0.4 (5.7)	
Temperature	°C (°F)	52 (126)	
CONSTITUENTS		Influent	Effluent
pH		7.14	7.84
Volatile Acids	mg/l CH_3COOH	2640	1180
Alkalinity	mg/l $CaCO_3$	2520	3350
COD	mg/l O	11,400	6700
BOD_5	mg/l O	--	2150
Soluble BOD_5	mg/l O	--	1770
Suspended Solids (SS)	mg/l	1650	1390
Volatile SS	%	61.4	60.0
Total Dissoved Solids	mg/l	4760	3730
Total Kjeldahl Nitrogen	mg/l	1150	1200
Ammonia Nitrogen	mg/l N	810	850

* Estimate

Thermal Reactor Parameters

Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

Mechanical Dewatering

Mechanical dewatering experiments were conducted on digested and undigested LPO conditioned primary and waste activated sludge blend. The studies were conducted to show how the dewatering characteristics of thermal conditioned sludge were affected by digestion.

Pressure Filtration --

Four filter press runs were conducted on the 0.78 m^2 (8.4 ft^2) pilot press and the results are summarized in Table 21. Three runs (12, 13, and 14) were conducted on thickened, undigested LPO conditioned sludge. Each of these tests were conducted at a pressure of 690 kPa (100 psi) while run times of 20, 60, and 90 min were used. Cake dryness increased from 39% at the 20-min run time to 58% at the 90-min run time. Filtrate quality was independent of run time. Filter yield decreased as the run times were lengthened. However, the 20-min cycle produced a cake having poor consistency. The inner portion of the cake was damp and sticky.

TABLE 21. PRESSURE FILTRATION OF LPO CONDITIONED PRIMARY AND WAS BLEND

Sludge Type	Run #	Filter Yield[a] kg/m²/hr (lb/ft²/hr)	Press Time min	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Consistency/ Discharge
Thickened Undigested Heatrate	12	8.98 (1.84)	60	14.1	13.1	1.078	0.078	99.4	53.2	Good/ Good
Thickened Undigested Heatrate	13	18.1 (3.71)	20	14.1	13.1	1.082	0.082	99.4	38.8	Fair/ Good
Thickened Undigested Heatrate	14	6.64 (1.36)	90	19.4	18.3	1.140	0.040	99.8	58.0	Good/ Good
Unthickened Digested[b] Heatrate	15	3.61 (0.74)	90	3.95	3.61	0.34	0.0006	99.9+	33.5	Poor/ Poor

[a]Cloth Medium: 1-P

[b]Digester Parameters

Temperature: 48°C (118°F)
Detention Time: 22 days
VS Loading:

Thermal Reactor Parameters

Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

TABLE 22. VACUUM FILTRATION OF UNDIGESTED, LPO CONDITIONED GRAVITY THICKENED PRIMARY AND WAS BLEND

Run #	Filter Yield[a] kg/m²/hr (lb/ft²/hr)	Cycle Time min:sec	Feed[b] %TS	Feed[b] %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake %TS	Discharge
24	29.2 (5.98)	2:00	10.19	9.19	1.12	0.12	98.7	40.8	Excellent
25	20.4 (4.17)	4:07	10.19	9.19	1.09	0.09	99.0	41.3	Excellent
26	16.4 (3.35)	6:38	10.19	9.19	1.09	0.09	99.0	41.5	Excellent

[a]Cloth Medium: KS-515

[b]Sludge Type: Thickened Heatrate

-2.1m (7ft) diameter Gravity Thickener
-No polymer added

Thermal Reactor Parameters

Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

Pressure filtration of the digested LPO conditioned sludge was not very successful. At a 90-min run time, the cake solids were only 33.5%. The wet nature of the cake resulted in poor operation. The cake had to be manually scraped from the fabric and washing was required. An attempt was made to conduct a test run on thickened, digested LPO conditioned sludge so that a direct comparison could be made on the effects of digestion on dewatering performance. The thickened, digested sludge had a solids concentration of 11% and the positive displacement feed pump was not able to maintain adequate filtering pressures. As a result, no experimental results were obtained.

Vacuum Filtration --

Six vacuum filtration test runs made on thickened LPO conditioned primary and waste activated sludge blend. Three of the runs were made on undigested sludge and the other three runs were on digested sludge. Several attempts were made to vacuum filter unthickened digested conditioned sludge but all fabrics clogged immediately. This sludge could not be dewatered by a vacuum filter.

Table 22 contains the results of three vacuum filter runs on thickened undigested LPO conditioned sludge. The sludge was thickened without the use of polymer and recoveries in the gravity thickener were on the order of 90%. The feed solids to the vacuum filter were in excess of 10%. The filter was operated at cycle time from 2 to 6.5 min and no conditioning chemicals were used. Cake solids from the filter were about 41% for all cycle times and in each run the cake had excellent discharge characteristics. The suspended solids recoveries were all 99% with a filtrate suspended solids of 1200 mg/l or less. The filter yield in $kg/m^2/hr$ ($lb/ft^2/hr$) ranged from 29.2 (5.98) for a 2-min cycle to 16.4 (3.35) for a 6.5-min cycle.

Table 23 presents the results of the three vacuum filter runs on the thickened, digested LPO conditioned blend. The sludge was conditioned with 1.5 g/kg (3 lb/ton) of cationic polymer and gravity thickened to 11.32% total solids. The suspended solids recovery for the gravity thickening step was greater than 95%. The vacuum filter was operated at cycle times ranging from 2 minutes to 6.5 min. No other conditioning chemicals were added during the filtration process. The cake solids ranged from 29 to 34% with the 2 min cycle time having the wettest cake. Filtrate quality was rather poor during the short cycle runs but the 65-min cycle filtrate contained only 400 mg/l SS (Run 29). The filter yields in $kg/m^2/hr$ ($lb/ft^2/hr$) decreased from 41.5 (8.5) at a 2-min cycle time to 21.0 (4.3) for a 6.5-min cycle time.

In comparing the effects of digestion of LPO conditioned sludge on vacuum filter performance, the data in Tables 22 and 23 indicate that digestion leads to a decrease in cake solids of 7 to 10 percentage points. However, filter yields are greater for the digested sludge. When comparing similar filter yields (Runs 25 and 29), the undigested sludge cake

TABLE 23. VACUUM FILTRATION OF DIGESTED LPO CONDITIONED, GRAVITY THICKENED PRIMARY AND WAS BLEND.

Sludge Type	Filter Run #	Filter Yield[a] $kg/m^2/hr$ $lb/ft^2/hr$	Cycle Time min:sec	Feed %TS	Feed %SS	Filtrate %TS	Filtrate %SS	Recovery %	Cake % TS	Discharge
65% Primary Sludge 35% WAS	27	41.3 (8.46)	1:59	11.32	10.94	0.67	0.27	97.5	29.2	Excellent
	28	28.1 (5.75)	4:15	11.32	10.94	0.72	0.32	97.1	33.9	Excellent
	29	21.0 (4.31)	6:30	11:32	10:94	0.44	0.04	99.6	33.5	Excellent

[a]Cloth Medium: KS515

Thermal Reactor Parameters
Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

0.56 m (22in) Diameter Gravity Thickener
Polymer: 1.5g/kg(3 lb/ton)
Detention Time: 90 min
Recovery: 95% SS

Digester Parameters
Temperature: 49°C(120°F)
Detention Time: 21.9 days

TABLE 24. SCROLL CENTRIFUGATION (DELAVAL, 35 CM DIAMETER) OF DIGESTED LPO CONDITIONED PRIMARY AND WAS BLEND

Run #	Flow l/s (gpm)	Polymer Dose g/kg (lb/ton)	Feed Solids %TS	Centrate SS mg/l	Cake Solids %TS	Recovery %SS	Relative Scroll Speed, rpm	Pool Depth cm (in)
1	1.3(20)	0	1.9	7,200	11	55	10	7.4(2.9)
2	1.3(20)	2.4(4.7)	2.0	170	19	99	10	7.4(2.9)
3	1.3(20)	2.6(5.2)	2.2	130	18	99	10	7.4(2.9)
4	1.3(20)	3(6.0)	2.0	500	18	97	10	7.4(2.9)
5	1.3(20)	3.8(7.6)	1.9	180	18	99	10	7.4(2.9)
6	1.3(20)	4.0(7.9)	1.9	720	26	96	10	6.9(2.7)
7	1.3(20)	5.0(10)	1.9	750	27	95	10	6.9(2.7)
8	1.3(20)	7.0(14)	1.9	660	29	96	10	6.9(2.7)
9	1.3(20)	11.5(23)	1.9	300	30	98	10	6.9(2.7)
10	1.3(20)	4.0(7.9)	1.9	800	24	95	14	6.9(2.7)

Bowl Speed: 2,250 rpm (1000 g's)

was 41% while the digested sludge cake was 34%. There was a 1.5-g/kg (3 lb/ton) cationic polymer demand for the digested sludge but no polymer was needed for the undigested sludge.

Scroll Centrifugation --

Two different centrifuges were tested on the digested LPO conditioned sludge blend. No attempts were made to dewater the undigested conditioned sludge. Data are presented in Tables 24 and 25. Table 24 summarizes the performance for the smaller 0.36-m diameter by 0.86-m scroll centrifuge (14-in diameter by 34 in). Table 25 data were developed on the 0.51-m diameter by 1.6-m (20-in diameter by 62 in) slow speed scroll centrifuge used in earlier studies.

The data in Table 24 for the 0.36-m (14-in) diameter scroll centrifuge were developed using a sludge feedrate of 1.3 l/s (20 gpm) and a bowl speed of 2250 rpm. Cationic polymer was used for conditioning in dosages ranging from 0 to 11.5 g/kg (23 lb/ton). The data in Table 24 show the effects of pool depth and relative scroll speed on centrifuge performance. At maximum pool depths (Runs 1-5), a polymer dosage of 2.4 g/kg (4.7 lb/ton) produced cake solids of 19% TS and a suspended solids recovery of 99%. Lowering the pool depth 0.5 cm (0.2 in) (Runs 6-9) resulted in a dryer cake, 26% TS, but the required polymer dose appeared to increase. A dosage of 4 g/kg (8 lb/ton) was needed to produce a 96% suspended solids recovery.

TABLE 25. SCROLL CENTRIFUGATION (KRUGER, 50 CM DIAMETER) OF DIGESTED LPO CONDITIONED PRIMARY AND WAS BLEND

Run #	Flow l/s (gpm)	Polymer Dose g/kg (lb/ton)	Feed Solids %TS	Centrate SS mg/l	Cake Solids %TS	Recovery %	Relative Scroll Speed, rpm
1	3.8(60)	2.0(4.0)	1.9	840	23.1	95	12
2	3.8(60)	4.3(8.5)	1.9	1140	24.3	93	12
3*	3.8(60)	7.4(14.7)	1.9	780	24.9	95	12
4	3.8(60)	3.2(6.4)	1.0	1020	26.6	87	9
5	3.8(60)	3.7(7.4)	1.0	810	20.4	90	9
6	3.8(60)	4.3(8.6)	1.9	870	26.7	95	9
7*	3.8(60)	8.8(17.5)	1.0	770	-	90	9
8*	4.4(70)	3.7(7.4)	1.1	1000	22.7	88	18
9	5.0(80)	2.6(5.1)	1.1	1270	23.1	85	18
10*	5.0(80)	4.0(8.0)	1.5	1540	24.6	87	18
11*	5.0(80)	6.5(13.0)	1.3	1310	26.6	87	18

*Excessive Centrate Foam

Bowl Speed: 1958 rpm (1100 g's)
Pool Depth: 10.2 cm (4.0 in)

Lower polymer dosages were not tested. Run 10 shows the effect of increasing the relative scroll speed on cake dryness. For the same operating conditions, the 4-rpm increase in relative scroll speed produced a slightly wetter cake at 24% TS.

The second scroll centrifuge was a much larger machine, 0.51 m (20 in) in diameter, and operated at a lower bowl speed, 1958 rpm. Flowrates of 3.8 to 5.0 l/s (60 to 80 gpm) were used and the pool depth was held constant at slightly less than maximum. Cationic polymer dosages ranged from 2 to 9 g/kg (4 to 18 lb/ton). The hydraulic capacity of this machine was so great that digested LPO conditioned sludge had to be stored for as much as a week in order to have sufficient quantity for test purposes. Also, data in Table 25 were developed in part by dewatering 30 m^3 (8000 gal) of the 45 m^3 (12,000 gal) pilot digester. These two operating procedures may have influenced the dewatering characteristics of the sludge. At a flowrate of 3.8 l/s (60 gpm), a polymer dose of 2 g/kg (4 lb/ton) produced a cake having 23% TS and a centrate of 840 mg/l suspended solids. Lowering the relative scroll speed produced a drier cake, 26% TS, but the polymer dose increased to 3 g/kg (6 lb/ton). At 5 l/s (80 gpm), a polymer dose of 2.5 g/kg (5 lb/ton) was needed to produce a 23% cake but the suspended solids recoveries decreased from 95 to 85%.

TABLE 26. BELT FILTER PRESS DEWATERING OF LPO CONDITIONED PRIMARY AND WAS BLEND AT MAXIMUM FLOW RATES

Belt[a] Press	Feed Sludge[b]	Flow m^3/hr (gpm)	Polymer Dose g/kg (lb/ton)	Feed Solids %TS	Combined Filtrate[c] mg/l SS	Cake Solids %TS	Solids Loading kg/hr/m (lb/hr/ft) Total Width	Solids Loading kg/hr/m (lb/hr/ft) Usable Width
Unit 1 0.5m Belt (20 in)	A	0.95 (4.2)	1.9 (3.7)	9.4	1,120	52.4	196 (132)	286 (192)
	B	1.4 (6.0)	4.6 (9.2)	1.7	780	38.3	54 (36)	79 (53)
Unit 2 0.6m Belt (24 in)	A	1.2 (5.5)	1.3 (2.5)	9.6	2,900	39	207 (139)	248 (167)
	B	2.6 (11.5)	2.0 (4.0)	1.7	1,070	34.7	92 (62)	112 (75)

[a] Belt Width: Total / Usable
Unit 1: 0.5m / 0.34m
Unit 2: 0.6m / 0.5m

[b] Sludge Type: A=Gravity Thickened Undigested 65% Primary, 35% WAS Blend
B=Unthickened Digested 65% Primary, 35% WAS Blend

Thermal Conditioning Parameters
Temperature: 200°C (400°F)
Pressure: 2758 kPa (400 psig)
Detention Time: 29 min
Air: 0.6 l/s (1.2 scfm)

[c] Filtrate (mg SS) plus wash water (mg SS) divided by feed rate.

Increasing the polymer dose, in an attempt to improve suspended solids recovery, was not successful because large amounts of foam were produced. Under conditions of heavy foaming, full-scale operation would not be possible since the foam carries a large amount of suspended solids out with the centrate.

Belt Filter Press --

Two belt filter press units of similar size were tested using the LPO conditioned blend. Both units had a belt width of about 0.5 m (1.6 ft). Cationic polymer was used to condition the sludge. The machines were tested side-by-side on two types of LPO conditioned sludge: unthickened-digested blend and thickened-undigested blend. Performance data for the presses are summarized in Table 26. Only one set of data is shown for each sludge. The amount of available sludge for testing was limited and only the best performance in terms of flow rate and polymer dose was determined by the test work. Actual test work was limited to one day and cake solids and filtrate data were not available until after the tests had been completed.

Data in Table 26 compare the performance of both units on the digested and undigested LPO conditioned sludge. The total belt width of the first unit was 0.5 m (1.6 ft) but the width of belt where the sludge was actually applied was only 0.34 m (1.1 ft). This value is adjustable, depending on the sludge, and such data are necessary in developing a scaling factor for larger units. Therefore, solids loading values, in kg/hr/m (lb/hr/ft) of belt width, are presented for both the actual and "usable" belt widths. The performance on the thickened undigested sludge was excellent. At a feed rate of 0.9 m^3/hr (4 gpm), this unit produced 52% TS cake at a polymer

dose of 2 g/kg (4 lb/ton). Digested sludge performance was not as good; at 1.4 m^3/hr (6 gpm), the cake solids were 38% TS and the polymer dose increased to 4.5 g/kg (9 lb/ton).

The solids in the true filtrate, as well as the solids in the belt wash water, were measured and reported as a concentration value using the sludge feedrate. For both sludges, the combined "filtrate" represented a suspended solids recovery of greater than 95%.

The other unit had a total belt width of 0.61 m (2 ft) but conditioned sludge was only applied to a width of 0.5 m (1.6 ft). Performance data at maximum flowrates are shown in Table 26. At a flow of 1.2 m^3/hr (5.5 gpm) of thickened, undigested sludge, a polymer dose of 1.3 g/kg (2.5 lb/ton) produced a cake having 39% TS. When digested-unthickened sludge was used, the flowrate increased to 2.6 m^3/hr (11.5 gpm) but the polymer dose increased 2 g/kg (4 lb/ton), producing a 35% TS cake. As before, the filtrate solids were combined with the belt wash water solids and expressed as a single concentration value.

Several unknown factors regarding these units include: scale-up to larger units, amount of wash water, belt life, resistence of belt to blinding and tearing, and ability to handle changes in sludge characteristics. These devices were relatively new to the American Market at the time of this study and operational experience was not available.

Vacuum Filter with Press --

The last dewatering device tested was a modified vacuum filter. This unit was a conventional vacuum filter that would advance intermittently. During the stop portion of the cycle, a diaphram located after the vacuum drum would apply pressure to captured solids. This device was of a stop/start nature; the air pressures in the diaphragm ranged from 414 to 690 kPa (60 to 100 psi) with stop times of 20 to 60 sec. Two sludges were dewatered via this unit: thickened-undigested LPO conditioned blend and digested LPO condtioned sludge that had been conditioned with 2 g/kg (4 lb/ton) of cationic polymer and allowed to thicken from 1.5 to 4.2%. Performance data are presented in Table 27.

The thickened undigested sludge was dewatered without addition of cationic polymers. Cake solids ranged from 48 to 60% TS and the combined filtrate for these runs was 410 mg/l SS. Polymer doses of 2.4 and 1.3 g/kg (4.8 and 2.5 lb/ton) were required. Filter yields were 25 to 31 kg/m^2/hr (5 to 6 lb/ft^2/hr); the yields were less for the higher cake solids values. The concentrated digested sludge did not require any additional conditioning. Cakes were produced ranging in total solids content from 44 to 48% and the combined filtrate had 190 mg/l of suspended solids. Filter yields were 14.9 kg/m^2/hr (3 lb/ft^2/hr). Digestion resulted in a sludge cake having 10 to 20 percentage points less in total solids content.

TABLE 27. MODIFIED VACUUM FILTRATION OF LPO CONDITIONED PRIMARY AND WAS BLEND

LPO Conditioned 65% Primary 35% WAS	Polymer Dose g/kg(lb/ton)	Feed %TS	Cake Solids Before Press % TS	Cake Solids After Press % TS	Composite Filtrate mg/l SS	Filter yield kg/m²/hr (lb/ft²/hr)
	2.4(4.8)		39.8	60.0		25.1(5.15)
Thickened	2.4(4.8)	12.7	35.6	51.0	410	31.1(6.37)
Undigested	2.4(4.8)		34.4	48.1		31.1(6.37)
	1.3(2.5)		40.0	52.6		27.9(5.72)
Concentrated	2.0(4.0)		33.6	48.5		10.4(2.14)
Digested	2.0(4.0)	4.2	32.9	48.1	190	14.9(3.06)
	2.0(4.0)		32.9	44.5		14.9(3.06)

Gravity Thickening

As described in detail earlier, another series of gravity settling tests were conducted on the LPO conditioned, digested blend. A 15-cm (6-in) diameter lucite column was used to measure the rate at which the 1.5-g/kg (3-lb/ton) polymer conditioned sludge would settle. Figure 11 plots the height of the sludge interface with time for a range of initial solids concentrations, 3.8 to 8.8% TS. A semi-log plot of settling velocity versus initial solids concentration gives a straight line as shown in Figure 12.

Using the settling velocity curve, the Coe Clevenger(4) equation was used to predict the surface area of a gravity thickener to concentrate a 1.5% SS sludge to 12% TS underflow with a polymer dose of 1.5 g/kg (3 lb/ton). For an LPO conditioned, digested (65% primary, 35% WAS) blend resulting from a 4.4 m^3/s (100 mgd) pure oxygen treatment plant, a gravity thickener with a surface area of 232 m^2 (2500 ft^2) would be needed; this means the diameter of a circular thickener would be 17.4 m (57 ft).

The results from the Coe-Clevenger equation were again verified on a continuous flow basis using the 0.56-m diameter by 1.5 m (22-in diameter by 59 in) gravity thickener. Digested LPO conditioned sludge was fed to the thickener at a flowrate to yield a solids loading rate predicted by the Coe-Clevenger model. Again, steady-state conditions were reached and a 0.38-m (15-in) sludge blanket level was maintained. Samples were taken after six hours of operation. The results from this test are presented in Table 28. The model was successfully verified and test results showed an underflow solids concentration of 11.7% TS. The overflow contained only 115-mg/l suspended solids for an overall recovery of 99% SS. The COD of this stream should be in the range of the soluble digester effluent value of 6700 mg/l found in Table 20.

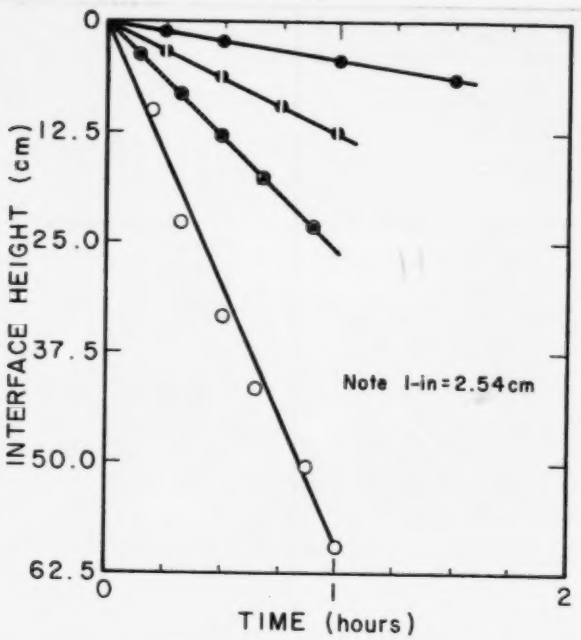


Figure 11. Gravity thickener interface height versus time for LPO conditioned blend.

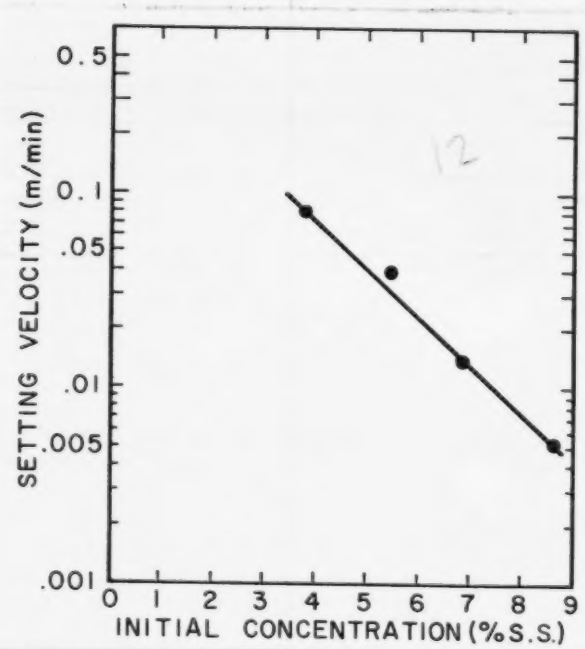


Figure 12. Gravity thickener settling velocity versus initial SS concentration for LPO conditioned blend.

TABLE 28. VERIFICATION OF THE COE-CLEVENGER THICKENING MODEL USING LPO CONDITIONED BLEND*

Variables	Coe-Clevenger Model	Run 4 6/17/77
Feed Solids, % SS	1.5	1.3
Underflow, % TS	12.0	11.7
Solids Loading, $kg/m^2/hr$ ($lb/ft^2/hr$)	19.6 (4.0)	27.8(5.7)
Surface Loading, $m^3/day/m^2$ (GPD/ft^2)	31 (760)	50(1,250)
Hydraulic Detention Time, hr	--	0.7
Polymer Dose, g/kg(lb/ton)	1.5 (3.0)	1.5(3.0)
SS Overflow, mg/l	--	115
SS Recovery, %	--	99.1
Duration of Test Run	--	6 hr

* Blend of 65% Primary and 35% Waste Activated Sludge

Pathogen Study

From the period April 27 to August 10, 1977, nine sets of grab samples were taken and analyzed for coliforms, salmonellae, and parasite eggs (Ascaris Ova). The results are contained in Table 29. A detailed summary of this study is presented in the Appendix. Each sample set contained three samples: influent, heatrate (thermal reactor effluent) and digester effluent samples.

As the case for the waste activated sludge LPO studies, it was not possible to insure that the sample line from the thermal reactor was free of organisms. High bacterial levels probably represent a poor sampling location and poor sampling technique. Based on a limited number of completed tests, the thermal conditioning-anaerobic digestion system was effective in the destruction of Salmonella sp. and Ascaris ova. However, indicator bacteria were present in the heatrate and effluent samples.

Laboratory Activated Sludge Studies

The recycle of high strength side streams from a thermal conditioning system may present a significant organic load on an activated sludge system. To predict what percentage of the COD in representative waste streams would be available as substrate to an activated sludge culture, three 30-liter (8-gal) laboratory fill-and-draw reactors were constructed. Operation of these reactors was as follows: Each day 7.6 liters (2 gal) of the mixed liquor were wasted, the air was shut off, and the contents were allowed to settle for one hour. Then 7.6 liters (2 gal) of the supernatant were wasted, and 15.1 liters (4 gal) of feed were added and the air was turned on. Samples of the feed, mixed liquor, and supernatant were taken; supernatant samples were assumed to represent the effluent. The air was on

TABLE 29. SUMMARY OF MICROORGANISM DATA FOR LPO CONDITIONED PRIMARY AND WAS BLEND

		Indicator Bacteria MPN/100 ml				Ascaris OVA/100ml	
Date	Sample	Total Coliform	Fecal Coliform	Fecal Strep.	Salmonella	Total	Viable
4-27	Influent	$9.3x10^8$	$9.3x10^8$	$3.9x10^6$	ND	ND	-
	Heatrate	<3	<3	< 3	ND	ND	-
	Effluent	23	4	$2.3x10^3$	ND	ND	-
5-11	Influent	$2.4x10^9$	$4.3x10^8$	$2.3x10^6$	$2.3x10^4$	25	19
	Heatrate	$9.3x10^2$	$9.3x10^2$	23	< 1	5	< 2
	Effluent	23	23	$2.3x10^2$	< 1	1	< 1
5-25	Influent	$4.6x10^9$	$4.3x10^8$	$7.5x10^6$	ND	ND	-
	Heatrate	<3	<3	43	ND	ND	-
	Effluent	23	4	230	ND	ND	-
6-22	Influent	$1.5x10^8$	$7.5x10^7$	$9.3x10^5$	$2.1x10^1$	26	26
	Heatrate	$9.3x10^3$	$2.3x10^3$	$4.3x10^2$	-	10	< 2.5
	Effluent	$4.3x10^2$	$2.3x10^2$	$4.3x10^2$	7	10	< 2.5
7-07	Influent	$2.4x10^9$	$4.3x10^8$	$2.4x10^7$	7	25	17
	Heatrate	$2.3x10^6$	$2.3x10^3$	$4.3x10^3$	<1	5	< 0.1
	Effluent	$2.3x10^3$	$2.3x10^1$	$2.3x10^2$	<1	5	< 0.1
7-22	Influent	$2.4x10^7$	$2.4x10^7$	$2.4x10^6$	ND	ND	-
	Heatrate	$2.4x10^4$	$9.3x10^3$	$2.4x10^3$	ND	ND	-
	Effluent	$2.4x10^2$	$2.4x10^2$	$7.5x10^2$	ND	ND	-
7-27	Influent	$1.4x10^7$	$1.4x10^7$	$9.3x10^6$	ND	ND	-
	Heatrate	$1.1x10^6$	$1.1x10^6$	$2.4x10^2$	ND	ND	-
	Effluent	$4.5x10^4$	$4.6.10^4$	$\geq 2.4x10^5$	ND	ND	-
8-10	Influent	$2.4x10^8$	$2.4x10^8$	$4.3x10^6$	$9.3x10^3$	ND	-
	Heatrate	$9.3x10^4$	$4.3x10^4$	$4.6x10^4$	< 1	ND	-
	Effluent	$9.3x10^2$	$9.3x10^2$	$7.5x10^2$	< 1	ND	-
Geometric Mean	Influent	$2.5x10^8$	$1.2x10^8$	$4.8x10^6$	$2.6x10^2$	25	22
	Heatrate	$9.2x10^3$	$3.0x10^3$	$3.2x10^2$	1	7	2.2
	Effluent	$5.6x10^2$	$2.1x10^2$	$1.9x10^3$	1.6	3	1.6

ND - Not Determined

continuously for 23 hr per day and typically, dissolved oxygen concentration was around 6 mg/l. This method results in a two-day hydraulic detention time and roughly a four-day mean cell residence time.

The results from two months of operation are presented in Table 30. The three feed samples taken to represent thermal conditioning side streams were: supernatant from gravity thickened heatrate (i.e. influent to anaerobic filter), anaerobic filter effluent, and supernatant from gravity thickened digested heatrate. The last feed sample also represents the characteristics of centrate from a mechanically dewatered, digested LPO blend.

TABLE 30. POTENTIAL OXYGEN DEMAND OF SIDE STREAM LIQUORS FROM LPO CONDITIONED PRIMARY AND WAS BLEND

Parameters For Activated Sludge Units	Material Fed To Laboratory Activated Sludge Units		
	Influent Liquor to Anaerobic Filter	Effluent Liquor from Anaerobic Filter	Supernatant from Gravity Thickened Digested Heatrate
Influent COD			
Total mg/l	10,200	7,000	3,200
Soluble mg/l	8,800	5,000	2,700
Effluent COD			
Total mg/l	6,300	3,500	2,200
Soluble mg/l	4,700	2,300	1,800
COD Removal			
Total %	38	50	31
MLVSS mg/l	2,500	1,100	300
COD Loading			
g COD/g MLVSS-day	2.0	3.2	5.3
Reactor Volume l (gal)	30.3(8.0)	30.3(8.0)	30.3(8.0)
Hydraulic Detention Time, days	2	2	2
Mean Cell Residence Time, days	4	4	4

As can be seen, from 30 to 50% of the COD was removed by these laboratory scale reactors. This indicates that recycle of these waste side streams may exert a significant organic load on an activated sludge system. It is interesting to note that both the anaerobic filter influent and effluent samples had between 3500 and 3900 mg/l of degradable COD. Taken at face value, the anaerobic filter did not provide much aid in reducing the organic load of the thermal conditioning side stream. However, the results of this test may not truly represent a full-scale system. The effect of a shorter hydraulic detention time in a full-scale system is not known and may be significant.

TABLE 31. SUMMARY OF HEAVY METALS DATA FOR LPO CONDITIONED PRIMARY AND WAS BLEND

Constituent		Influent		Heatrate		Effluent	
		Total mg/kg	Soluble mg/kg	Total mg/kg	Soluble mg/kg	Total mg/kg	Soluble mg/kg
Cadmium	Cd	39.2	0.006	61.8	0.006	87.5	0.005
Copper	Cu	760	0.02	980	0.02	1560	0.03
Lead	Pb	680	0.03	840	0.05	1310	0.04
Nickel	Ni	160	0.21	180	0.15	310	0.19
Silver	Ag	31.3	0.009	50.9	0.01	52.6	0.013
Zinc	Zn	1670	0.01	1960	0.20	3690	0.17
Mercury	Hg	3.91	0.0002	3.82	0.0002	6.69	0.0002
Arsenic	As	11.2	0.003	16.7	0.051	21.9	0.034
Total Solids		3.83%	--	2.75%	--	1.60%	--

Heavy Metals

Two 1-liter grab samples were taken May 25, 1977, and analyzed for the following metals: arsenic, cadmium, copper, lead, mercury, nickel, silver, and zinc. The data are shown in Table 31. Total metal concentration is expressed on a dry weight basis and soluble metal concentration as mg/l. The apparent increase in total metal concentration is related to the destruction of solid material following thermal conditioning and anaerobic digestion. Thus, less dry material remains and the ratio of metal weight to dry weight increases. The soluble concentrations of arsenic and zinc were increased by the thermal conditioning process.

PHASE III

The third phase of research was conducted primarily to study the manufacturer's odor control system. The thermal conditioning reactor was operated per the manufacturer's recommendations regarding the amount of air flow. Sufficient air was added to produce a 5% oxidation of the influent COD. The reactor temperature was lowered to 193°C (380°F) but the pressure and hydraulic detention time were maintained at 2758 kPa (400 psi) and 29 min.

The odor control system captured the gas stream coming off the gravity decant tank. A two-stage system was used. First a counter-current water scrubber was used to cool the gas and remove water vapor and soluble organic gases; this was followed by activated carbon adsorption. These studies were conducted using thickened waste activated sludge from the UNOX pilot plant. The study was conducted from October 17 through December 21, 1977. Additional studies were also conducted on digestion of the decant liquor from LPO conditioned WAS, filtration of LPO conditioned WAS, and centrifugation of a blend of digested primary and LPO conditioned WAS.

TABLE 32. DIGESTER RESPONSE TO DECANT LIQUORS FROM LPO CONDITIONED WAS (NOV. 15 - DEC. 21, 1977)

Performance	Units	Digester
COD Removal	%	42.0
Methane Production	m^3/kg (ft^3/lb) COD Removed	0.29(4.7)
VS Production	kg/kg (lb/lb) COD Removed	0.24(0.24)
Operation		
Volume	m^3(gal)	45.4 (12,000)
Hydraulic Detention Time	days	19.7
VS Loading	kg/m^3/day (lb/ft^3/day)	0.016 (0.001)
COD Loading	kg/m^3/day (lb/ft^3/day)	0.80 (0.05)
Gas Production	m^3/day (ft^3/day)	7.36 (260)
Methane Content	%	65.9
Temperature	°C (°F)	48 (119)

Constituents		Influent	Effluent
pH		5.80	7.49
Suspended Solids	mg/l	480	3440
Volatile Solids	%SS	68.9	60.0
Total COD	mg/l 0	17,000	9860
Soluble COD	mg/l 0	14,300	4600
Total BOD_5	mg/l 0	--	2860
Soluble BOD_5	mg/l 0	--	1570
NH_3-N	mg/l	560	1200
TKN	mg/l	2000	1600
Volatile Acids	mg/l	1650	840
Alkalinity	mg/l	540	4060

Stabilization: Anaerobic Digestion

The digestion portion of this study was conducted on decant liquors from the gravity separation of LPO conditioned waste activated sludge. The digester was fed the same material that had been treated by the anaerobic filter in earlier studies. The reason for this course of operation was twofold. First, the earlier results indicated that the anaerobic filter could remove only 40% of the applied COD. Literature results(3) on a similar sludge indicated 70% COD removals. By operating the digester on decant liquor at a 20-day hydraulic detention time, the COD removals should be maximized. Secondly, a possible treatment sequence at a full-scale plant could entail thermal conditioning of waste activated sludge, gravity separation, and blending of the decant liquor with raw primary sludge for anaerobic digestion. If the decant liquors could be digested alone without any problems, then such a blend could also be assumed to digest successfully.

Performance of the completely mixed pilot digester is presented in Table 32. Data on the thickened WAS influent to the reactor is not presented in Table 32. The reported influent data correspond to the decant liquors from the LPO conditioned sludge; this liquor was fed directly to the digester. The hydraulic detention time was 19.7 days and the reporting period of November 15 through December 21 corresponds to nearly 1.5 digester detention times. Operation of the digester was stable; effluent pH average 7.5 despite the typically high volatile acids concentrations noted in the other phases of this study. The normal digestion parameter of volatile solids loading is rather meaningless in this instance due to the efficiency of the decant tank in removing solids from the conditioned sludge. Digester temperature was maintained in the thermophilic range.

The digester was successful in removing 42% of the applied COD to an effluent concentration of 10,000 mg/l. The soluble COD dropped from an influent value of 14,300 mg/l to the effluent concentration 4,600 mg/l. The amount of volatile solids produced during the digestion was measured as 0.24 kg per kg of COD removed. Methane production averaged 0.29 m^3/kg (4.7 ft^3/lb) of COD removed. The low gas production values are due in part to the somewhat sporadic feeding of the digester during this phase of the study. The performance of the pilot digester in terms of COD removal is comparable to the performance of the anaerobic filter on a similar sludge (Table 9). The difference between the two processes is the required reactor volume which is about ten times greater for a digester than for an anaerobic filter.

In order to determine the maximum amount of COD that can be removed from the thermal conditioning decant liquors, the pilot digester continued operation for 22 days after the last day of regular feeding. The reactor temperature was maintained at 49°C (120°F) and the contents were kept completely mixed. Effluent samples were taken on a routine basis and gas production was monitored. The effluent COD values from these samples are presented graphically in Figure 13. The data show that there was essentially little change in the COD during the 22-day period. Gas production dropped to very minor levels within 3 days after regular feeding had ended. This leads to the conclusion that maximum COD removal by an anaerobic process on thermal conditioning decant liquors is approximately 45%. Also, a great majority of this COD removal can be accomplished in as little as 2 to 3 days by using an anaerobic filter.

An unexpected operational problem was encountered during this phase of the study. After 17 days of digesting decant liquors, the gas blower used to mix the digester became clogged with a tar-like substance. At the time, it was not known whether the buildup was cumulative or was due to a change in feed sludge. However, 40 days later the same problem reoccurred. The blower was completely frozen and had to be thoroughly cleaned with an industrial solvent. No reason can be presented for the formation of this material, but it appears to be caused by the digestion of the decant liquors.

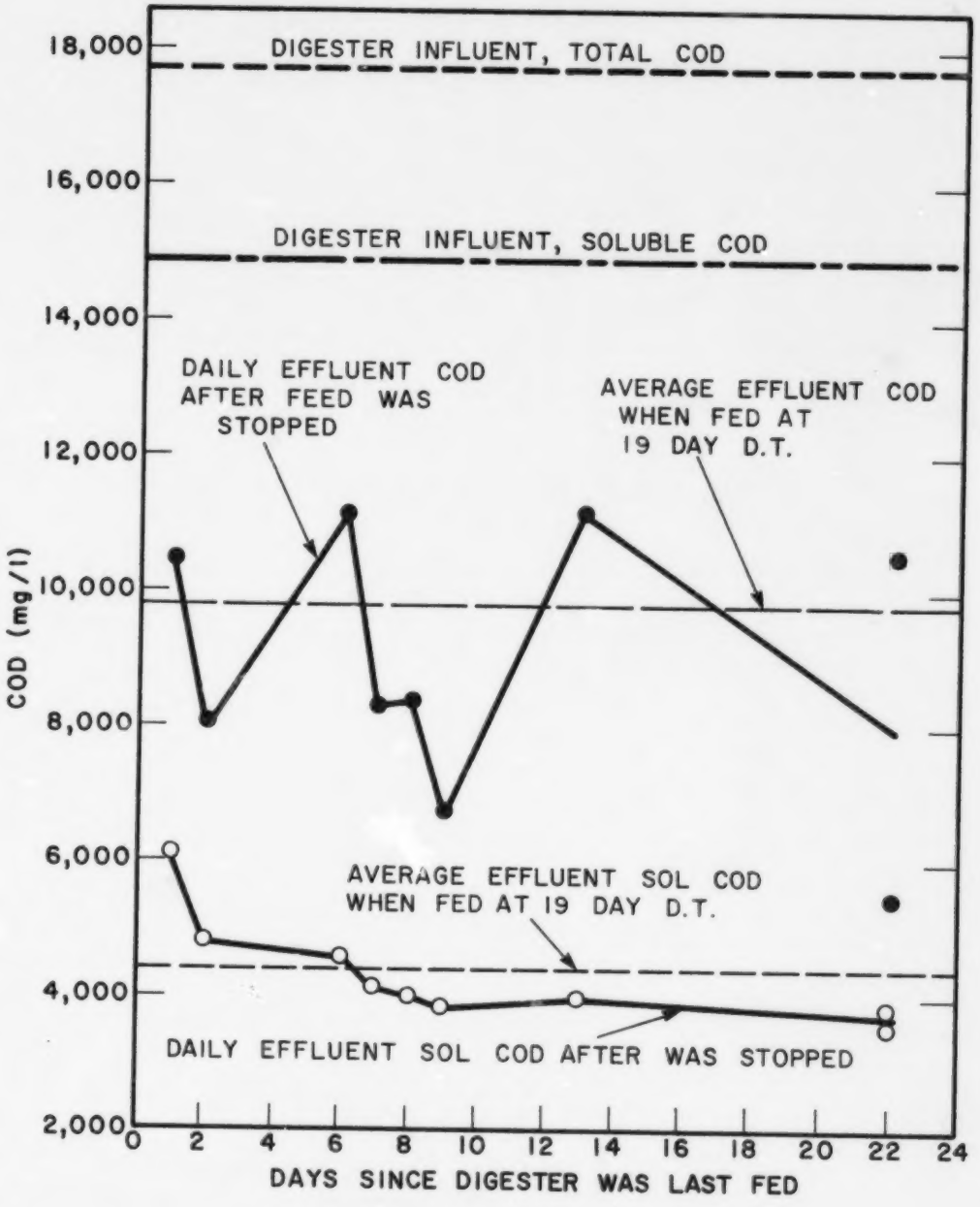


Figure 13. Extended digestion of decant liquors from LPO conditioned WAS

Stabilization: Anaerobic Filtration

The anaerobic filter was not operated during this phase of the study. There was a minimal supply of thickened waste activated sludge and the digestion of decant liquor was considered more important. The results from the first phase of this study will be used to define anaerobic filter performance on decant liquors from LPO conditioned WAS. These results were presented in Table 9.

Mechanical Dewatering

Mechanical dewatering studies were only conducted on the LPO conditioned, thickened, and undigested sludge. The digester was operating on decant liquors and the solids concentration of the effluent was only 0.3%. Consequently, mechanical dewatering studies were not conducted on this sludge. Pressure filtration and vacuum filtration studies were conducted on the thickened, conditioned sludge. Scroll and basket centrifuges were used to dewater a blend of thickened-undigested, LPO conditioned WAS and digested primary sludge.

Vacuum and Pressure Filtration --

The filter press tests were conducted on the 0.78-m^2 (8.4-ft^2) unit; pressures of 690 kPa (100 psi) were used and cycle times of 40 and 90 min were studied. Vacuum filter studies were conducted on a 1-m (3-ft) diameter by 0.3-m (1-ft) wide unit. The performance data for both units are shown in Table 33. Data for the effect of storage time in the decant tank on dewatering characteristics are also presented.

For pressure filtration, the long storage time resulted in a cake having a total solids content of 48%. Sludge held in the decant tank for a shorter period of time resulted in pressure filter cake having 44% TS (Run 2). Both cakes exhibited good discharge characteristics from the fabric and conditioning chemicals were needed. The "short storage" sludge, however, had a pressure filter cycle time of only 40 min and a yield of 10.6 kg/m^3/hr (2.16 lb/ft^2/hr) versus a cycle time of 90 min and a yield of 5.0 kg/m^2/hr (1.03 lb/ft^2/hr) for the "long storage" sludge.

Optimal vacuum filtration performance on long storage time sludge produced a cake having 29% TS and a filter yield of 19.6 kg/m^2/hr (4.0 lb/ft^2/hr). Sludge with a shorter storage time resulted in a similar cake solids of 30%, but only half the filter yield, 9.3 kg/m^2/hr (1.9 lb/ft^2/hr). Suspended solids recovery was more of a problem with the "short storage" sludge. For both cases, the discharge characteristics of the sludge were excellent and no conditioning chemicals were required.

The results from these studies are limited but they do indicate that sludge stored in the decant tank for long periods of time appears to have slightly improved dewatering properties than sludge stored for a shorter period of time. Also, a longer storage time resulted in a thicker sludge; 11% vs 8% TS. It should be noted that there were no apparent operational problems in storing the sludge for prolonged periods in the bottom of the decant tank.

TABLE 33. EFFECT OF STORAGE TIME ON DEWATERING THICKENED, UNDIGESTED LPO CONDITIONED SLUDGE.

Filtering Device	LONG STORAGE TIME					SHORT STORAGE TIME				
	Feed %TS	Cake %TS	Cycle Time,min	Filter Yield kg/m²/hr (lb/ft²/hr)	Recovery %	Feed %TS	Cake %TS	Cycle Time,min	Filter Yield kg/m²/hr (lb/ft²/hr)	Recovery % SS
Vacuum Filter										
Run 1	10.90	29.0	2.4	19.5 (4.0)	96.1	7.06	32.0	2.0	15.1 (3.1)	61.0
Run 2	11.60	29.7	4.0	21.0 (4.3)	73.0	7.23	30.9	3.0	11.2 (2.3)	59.9
Run 3	11.60	28.8	6.8	14.6 (3.0)	93.2	7.92	29.6	4.5	9.3 (1.9)	90.7
Run 4	-	-	-	-	-	7.37	31.0	6.0	10.3 (2.1)	88.7
Pressure Filter										
Run 1	11.3	47.9	90.0	5.0 (1.03)	99.8	8.25	41.3	90.0	4.5 (0.92)	99.0
Run 2	-	-	-	-	-	8.01	43.9	40.0	10.5 (2.16)	99.2

* LPO Conditioned Solids were stored in the bottom of the Gravity Separator.
Long Storage Time corresponds to several days while Short Storage Time corresponds to overnight storage.

TABLE 34. BASKET CENTRIFUGATION OF DIGESTED PRIMARY AND UNDIGESTED LPO CONDITIONED WAS BLEND

Run #	Feed %SS	Polymer Dose g/kg (lb/ton)	Cake %TS	Centrate mg/l SS	Recovery %
1	3.35	1.5 (3.0)	20.0	2800	92
2	3.35	1.8 (3.6)	21.4	5840	83
3	3.60	2.1 (4.2)	21.9	1900	95

All runs made at 1400 rpm with a 3.2 l/s (50 gpm) feed rate.

TABLE 35. SCROLL CENTRIFUGATION OF DIGESTED PRIMARY AND UNDIGESTED LPO CONDITIONED WAS BLEND (KRUGER, 50 CM DIAMETER)

Run #	Sludge Flow l/s(gpm)	Feed %SS	Polymer Dose g/kg(lb/ton)	Cake %TS	Centrate mg/l SS	Recovery %	Relative Scroll Speed, rpm
1	5.0(80)	3.40	3.7 (7.4)	21.9	3100	91	20
2	5.0(80)	3.40	3.7 (7.4)	23.5	4600	86	20
3	5.0(80)	3.40	7.4 (14.7)	25.4	9400	72	15
4	3.8(60)	3.40	4.9 (9.8)	25.9	5100	85	15
5	3.8(60)	3.40	9.8 (19.6)	26.3	3900	89	15
6	3.8(60)	3.40	4.9 (9.8)	22.6	3200	91	20

All runs made at bowl speed of 1960 rpm with pool depth slightly less than maximum.

Basket and Scroll Centrifugation --

A 1.2-m (48-in) diameter basket centrifuge and a 0.5-m (20-in) diameter by 1.6-m (62-in) low speed scroll centrifuge were used for these studies. A blend was made using thickened LPO conditioned waste activated sludge and digested primary sludge from the JWPCP. The blend ratio corrresponds to a weight ratio of the sludge solids of 70% primary and 30% WAS. The performance data for these tests are presented in Tables 34 and 35.

All test runs using the basket centrifuge (Table 34) were made at a sludge feed rate of 3.2 l/s (50 gpm). The basket was operated at 1400 rpm producing 1,350 g's at the bowl wall. Cationic polymers were used to condition the sludge. A polymer dose of 2 g/kg (4 lb/ton) produced a cake solids with 22% TS. Centrate quality was 1,900 mg/l suspended solids with 95% recovery. The basket centrifuge run times were approximately 13 min under these conditions. The characteristic odor of thermal conditioned sludge was evident during these tests.

The low speed, scroll centrifuge data are presented in Table 35. All runs were made at a bowl speed of 1,960 rpm, producing a force of 1100 g's at the bowl wall. Cationic polymer was used for conditioning. Pool depth was held at slightly less than maximum for these test runs. A flow rate of 5.0 l/s (80 gpm) and a polymer dose of 3.7 g/kg (7.4 lb/ton) produced a 22% TS cake but suspended solids recoveries were marginal at about 90%. Lowering the relative scroll speed did increase cake dryness but required an increase in polymer dose and resulted in poorer suspended solids recoveries (72% SS). Also, some foam was found in the centrate. When the sludge feed rate was reduced to 3.8 l/s (60 gpm), the performance did not improve and was degraded in terms of polymer dose and suspended solids recovery.

Odor Control Studies

The main objective of the phase of the study was to evaluate the effectiveness of the manufacturer's recommended odor control system. The characteristic thermal conditioning odors are due to volatile, low molecular weight hydrocarbons which include various classes of compounds such as alcohols, aldehydes, ketones, and organic acids. Several of these compounds have a very low odor threshold, meaning that the odors are noticeable at very low concentrations. These compounds are not the typical hydrogen sulfide and mercaptan compounds normally associated with wastewater treatment plant odors. Thermal conditioning produces the low molecular weight compounds through oxidation and hydrolysis reactions of complex proteins, fats, carbohydrates, etc. found in wastewater sludges.

In these studies, only the off-gases from the gravity decant tank were treated. Other uncontrolled sources were evident during the course of the study and would require consideration in a permanent installation. Due to the volatile nature of the odorous low molecular weight compounds, the dewatered sludge cake and the various liquid side-streams emitted an odor which was very noticeable during all dewatering and digestion studies.

The odor control system used in these studies consisted of a single-stage water scrubber followed by carbon adsorption. The water scrubber was designed to remove water soluble organic substances, condensible odor-causing organic compounds, and entrained water droplets from the moist gas stream emanating from the decant tank. For optimum use of the carbon beds, the vapor was passed through a cooler in order to lower gas temperature to 21° to 24°C (70° to 75°F). A single pass through adsorption unit was used

TABLE 36. ANALYSIS OF LIQUID SIDESTREAMS FROM THE TWO-STAGE ODOR CONTROL SYSTEMS

Constituent	Water Scrubber Effluent	Condensed Steam From Carbon Regeneration
Suspended solids	3 mg/l	40 mg/l
COD	120 mg/l	2550 mg/l
BOD_5	70 mg/l	600 mg/l
Volatile Acids	--	50 mg/l as CH_3COOH
pH	--	5.05

to remove remaining low molecular weight compounds. Following exhaustion of the carbon bed, low pressure steam was used to regenerate the carbon.

The size of the odor control system was based on a 0.3-l/s (5-gpm) sludge flow and sufficient air added during the low pressure oxidation conditioning process to produce 5% oxidation. The vapor flow from the decant tank was held at 14.2 l/s (30 scFm). The counter-current water scrubber used 0.14 kg (0.3 lb) of water per min of vapor flow. The contact time in the scrubber was approximately 1 second. Twenty-three kg (50 lb) of granular activated carbon were used in the carbon adsorption unit and the empty bed vapor contact time was approximately 3 sec. Regeneration of the spent carbon was accomplished using 0.45 kg (1 lb) of 69-kPa (10-psi) steam per 0.45 kg (1 lb) of carbon. Table 36 contains a summary of the chemical quality of the water scrubber discharge and the condensed steam from the carbon regeneration. These waste streams would normally be recycled back to the treatment plant.

In order to monitor the effectiveness of this odor control system and to establish the treatment capacity of the carbon before breakthrough, routine samples were taken three days per week. Sanitation District personnel collected samples and analyzed them for threshold odor concentration levels using an odor panel. Employees of Zimpro, Inc. also took samples and used a gas chromatograph to analyze the concentration of oxygen, nitrogen, carbon monoxide, total hydrocarbons, and methane. The odor concentration of the gas stream is normally dependent, to a large degree, on the concentration of total hydrocarbons. Three sampling locations were used; the gas from the decant tank, the discharge from the water scrubber, and the carbon adsorption bed discharge. Data are presented in Table 37.

The results of this study show that the two-stage system was successful in removing 97% of the incoming odor units. The median value of the odor dilution ratio of the gas in the gas discharge stream was 230 (see Table 37).

TABLE 37. PERFORMANCE OF THE TWO-STAGE ODOR CONTROL SYSTEM

Hours Since Regeneration	DECANT TANK VAPORS		WATER SCRUBBED DISCHARGE		CARBON BED DISCHARGE		% ODOR UNIT REMOVAL	
	Z* x 10^{-3}	Hydrocarbons PPM as CH_4	Z* x 10^{-3}	Hydrocarbons PPM as CH_4	Z* x 10^{-3}	Hydrocarbons PPM as CH_4	Water Scrubber	Carbon Bed
0.5	0.52	300	0.22	390	0.03	0	59	94
1.5	4.5	450	0.69	370	0.22	0	85	95
4.0	21.7	1,180	6.4	1,000	Trace	55	70	99+
6.0	5.9	830	1.38	670	0.04	200	79	99
8.0	31.5	770	31.5	630	0.230	270	0	99+
10.0	13.8	1,520	8.4	1,320	0.048	520	39	99+
11.1	217	1,130	77	1,120	9.9	770	65	95
13.1	217	1,340	15.8	1,070	.74	1,020	93	99+
16.2	6.9	1,340	39.4	1,250	.056	1,060	43	99+
1.0	3.0	--	0.59	--	.017	--	80	99+
2.0	32.5	2,320	7.5	1,380	.220	1,380	77	99+
4.0	12.8	--	2.27	--	.045	--	82	99+
6.3	12.8	840	2.37	610	.099	540	82	99+
7.3	8.4	1,100	7.0	650	.21	650	16	98
9.3	4.7	1,260	3.4	700	.43	690	29	91
10.3	10.8	--	3.0	--	.23	--	73	98
12.3	17.7	--	3.0	--	.69	--	83	96
15.1	4.9	1,600	3.2	450	.23	900	36	95
16.1	10.8	1,700	6.4	910	1.08	950	41	90
23.3	16.8	1,990	4.4	1,150	.74	860	74	96
25.3	15.8	2,310	3.2	1,310	.25	1,150	80	98
1	21.7	1,330	9.9	810	.89	740	55	96
3	29.6	1,090	23.7	850	1.58	860	20	95
5	46.3	1,570	2.27	1,020	1.68	970	95	96
6	16.8	1,610	3.5	930	2.30	1,000	79	86

*Z, the odor dilution ratio, is the sum of the volume of an odorous gas sample and the clean air required to dilute the odor to the detection threshold divided by the volume of odorous gas sample. See ASTMD 1391-78.

TABLE 38. EFFECT OF DIGESTION ON ODOR CONCENTRATION FOR LPO CONDITIONED WAS

Digestion	Odor Dilution Ratio (Z)X10^{-3} Maximum	Minimum	Average	Odor Unit Reduction	H_2S Concentration	Number of Samples
Influent (Decant Tank Liquors) 54°C (130°F)	69	0.45	10.8	--	--	23
Effluent 49°C (120°F)	16.8	1.28	3.9	64%	50-125 mg/l	7

The water scrubber portion of this system was effective in removing water-soluble organic compounds, resulting in an average 68% reduction in odor units. It was not possible to determine the breakthrough characteristics of the carbon bed because the system was operated on an intermittent basis and for every four to six hours when the bed was in operation, it was out of service for 40 hr. When the bed was regenerated with low pressure steam, it did appear to recover its adsorption capabilities.

The effect of anaerobic digestion on the odor levels of the thermal conditioned decant liquors was also evaluated. Based on seven samples, the odor dilution ratio of a gas sample above the digested sludge decant liquor was 4,000. This value can be compared to the average odor dilution ratio of a gas sample from the decant tank of 11,000. Table 38 contains a comparison of the odor unit concentration for both waste streams.

Digested decant liquors had a significant concentration of hydrogen sulfide, 50 to 125 mg/l. Two methods were used to eliminate the hydrogen sulfide (Table 39). The addition of 200 mg/l of hydrogen peroxide was successful in reducing the hydrogen sulfide concentration to zero and reduced the odor unit concentration dramatically. In order to determine if hydrogen sulfide was the major odor-causing agent in the digested sludge, zinc was added to the digester sludge to remove hydrogen sulfide as zinc sulfide precipitate. This method was also successful in removing hydrogen sulfide and reducing odor unit levels. The odor unit removals were greater when hydrogen peroxide was used, indicating that some odorous compounds were oxidized by the hydrogen peroxide.

TABLE 39. CONTROL OF DIGESTED LPO DECANT LIQUOR ODORS WITH HYDROGEN PEROXIDE[1]

Contact Time (Min)	Background Digester Effluent		Hydrogen Peroxide 200 mg/l		Hydrogen Peroxide 400 mg/l		Zinc 100 mg/l	
	Z^2	H_2S (mg/l)	Z^2	H_2S (mg/l)	Z^2	H_2S (mg/l)	Z^2	H_2S (mg/l)
0	5900	125	N/A[3]	N/A	N/A	N/A	N/A	N/A
2	N/A	N/A	69	0	99	0	990	0
30	N/A	N/A	32	0	69	0	--	--
60	N/A	N/A	8.9	0	24	0	--	--

Note: 1) Odor samples were collected from vapors given off by a 190-liter (50 gal) sample of 49°C (120°F) digester effluent. Cooling of sludge during 60-min contact time resulted in some of the indicated odor reduction.
2) Odor dilution ratio
3) N/A - Not applicable

SECTION 4

ENERGY ANALYSIS

INTRODUCTION

This analysis will be limited to the energy demands and energy credits of anaerobic digestion and thermal conditioning. No attempts will be made to quantify the energy demands for prethickening waste activated sludge, operating mechanical dewatering equipment or aerobically treated recycle liquors from the thermal conditioning process. The major energy demand in this analysis is for producing steam used in the thermal conditioning process. Electrical demands for the high pressure pumps and air compressors also represent a significant thermal conditioning energy demand. In the anaerobic digestion process, the energy needed for maintaining temperatures and for mixing are evaluated. The energy credits are limited to the Joule (BTU) value of the gas produced by the anaerobic digesters and the anaerobic filters. Any losses incurred while using this gas for producing other forms of energy will not be evaluated. For comparative purposes, similar energy balances are provided for: digestion alone, conventional thermal treatment and thermal pretreatment.

THERMAL CONDITIONING ENERGY DEMANDS

The trailer-mounted Zimpro pilot unit used for the actual field test was not designed to be energy efficient. The data collected on the amount of energy used to operate this test unit does not realistically demonstrate the energy requirements of a full-scale installation. The energy required to maintain reactor temperatures in the pilot unit was approximately twice that expected for a well designed installation. Measurements of electrical power were not made on the test unit.

The amount of steam required to maintain reactor temperatures is largely a function of the heat exchangers. All manufacturers of thermal conditioning equipment use heat exchangers to recover as much heat as economical from the hot sludge leaving the reactor. Extremely large heat exchangers could be constructed to transfer nearly all the heat from the conditioned sludge to the influent sludge but the capital costs and the added pumping headloss and maintenance problems would not be practical. For this reason, the temperature difference between incoming sludge and the desired reactor temperature must be overcome with the introduction of compressed steam. In this analysis the temperature difference will be

assumed to be as low as 22°C (40°F) and as high as 44°C (80°F) for a typical installation. This will demonstrate the impact of heat exchanger design on overall energy efficiencies. A value of 14,000 J/l (50 Btu/gal) will be used to account for heat losses through radiation. No further credits will be given for any exothermic oxidation reactions in the process.

The specific heat of sludge will be assumed to be the same as for water, ie., 4,184 J/kg°C (1 Btu/lb°F). The efficiency of a boiler for producing steam is assumed to be 80% of the fuel energy. For 3.8 liters (1 gal) of sludge with a heat exchanger temperature difference of 22°C (40°F), and a 14,000-J/l (50 Btu/gal) heat loss, the energy demand for maintaining reactor temperature is 140,000 J/l (500 Btu/gal). For a 44°C (80°F) temperature difference, this value becomes 250,000 J/l (900 Btu/gal). These values are realistic, based on published information and operating data from full-scale installations.

The electrical energy demands are a function of the type of thermal conditioning process; low pressure oxidation requires more electrical power than does heat treatment conditioning. The electrical demands for the high pressure air compressors used for low pressure oxidation require 11,120 J/l (40 Btu/gal) when operated to produce 5% oxidation of organics. This value is an estimate based on actual operating experience. The remaining electrical demands are common to both types of thermal conditioning. An estimated 9,730 J/l (35 Btu/gal) is needed mainly for high pressure pumps, and also for grinders, instrumentation, lighting, etc. The total electrical energy demands are for the amount of power used as electricity and do not include any losses encountered in producing electrical power.

A major sensitivity of the thermal conditioning process is the solids concentration of the influent sludge. All energy demands are expressed in terms of J/l (Btu/gal) of sludge. For a given weight of sludge solids, at lower solids concentrations, more volume of water is present and must be heated to reactor temperatures. The magnitude of this sensitivity is demonstrated by the following example (assuming heat exchanger efficiency is unaffected by the solids concentration). Heat treatment conditioning with a heat exchanger temperature difference of 22°C (40°F) requires 150,000 J/l (535 Btu/gal) of energy. One kg of dry waste activated sludge solids at 3.5% TS is the basis for this comparison. If the same solids were at 4% TS, there would be 13% less volume of liquid sludge and the energy savings would be 243,000 J (230 Btu). Conversely, if the solids concentration were to drop to 3.0% TS, there would be 16% more volume of liquid sludge and the energy demand would be increased 317,000 J (300 Btu).

ANAEROBIC DIGESTION ENERGY DEMANDS AND CREDITS

The major energy demand for the anaerobic digestion process is the heat required to bring the raw sludge up to reactor temperatures and to maintain temperatures throughout the digestion period against heat losses.

The specific heat of sludge is assumed to be the same as water, 4,184 J/kg°C (1 Btu/lb°F). The temperature of raw sludge is assumed to be 24°C (75°F). The energy requirements for overcoming heat losses is calculated using actual operating experience of five 1.42 x 10^4-m^3 (3.75 x 10^6-gal) mesophilic digesters at the JWPCP. The average ambient temperature at the JWPCP is 18°C (65°F) and the digestion period is 15 days. Direct injection of live steam is used to heat the JWPCP digesters. Steam boiler efficiencies are assumed to be 80%. Electrical power for digester mixing is taken into account but it amounts to about 1% of the heating requirements. For mesophilic digestion at a 20-day hydraulic detention time, a value of 90,350 J/l (325 Btu/gal) will be used based on JWPCP data. For 20-day thermophilic digestion, this value increases to 189,040 J/l (680 Btu/gal); 58,380 J/l (210 Btu/gal) is needed to overcome radiation losses during the 20-day detention time.

The energy demands for the anaerobic filter are limited to electrical demands for pumping. These values are relatively small and will be neglected.

INDIVIDUAL TREATMENT SYSTEM EFFICIENCY

Baseline Systems

Figure 14 presents the energy balance for conventional or baseline treatment systems. For anaerobic digestion without any thermal conditioning, mesophilic digestion of thickened waste activated sludge at a 20-day hydraulic detention time was determined in earlier studies to be more energy efficient than thermophilic digestion. For the 65% primary and 35% thickened WAS blend, mesophilic digestion will also be used as a baseline. The energy values in Figure 14 are based on a mass of 91 metric tons (100 short tons) of dry sludge solids influent to the digesters. Volatile solids destruction and gas production values for WAS are based on earlier studies(2), and gas production for digestion of primary sludge is based on actual operating experience at the JWPCP. Both of these treatment schemes produce more Joules (Btu's) of digester gas than are needed to operate the system. There is a net surplus of energy, 4.3 x 10^{11} J (4.05 x 10^8 Btu) for the primary/WAS blend and 2.1 x 10^{11} J (1.95 x 10^8 Btu) for the thickened WAS.

Conventional thermal treatment systems usually follow anaerobic digestion if digestion is used at all. The energy balance for this process sequence is shown in Figure 14 for both thickened WAS and a blend of 65% primary, 35% thickened WAS. These are calculated results since these sequences were not actually experimented with in our program. The effect of the energy required to operate the thermal conditioning process is quite evident. Addition of thermal treatment causes the process sequence for WAS to become a net consumer of energy.

The values in Figure 14, also show how the efficiency of the thermal conditioning heat exchanger has a pronounced effect on the overall energy efficiency of the treatment system.

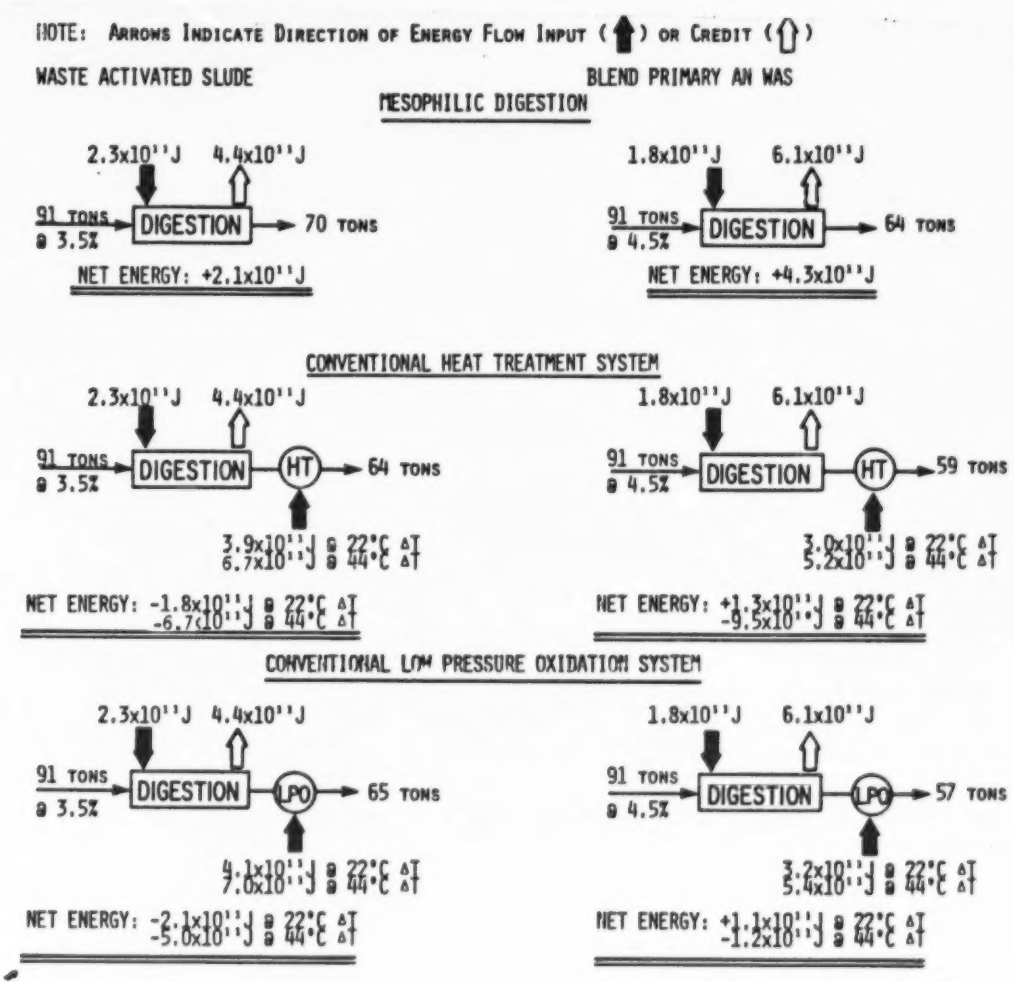


Figure 14. Energy balances for anaerobic digestion and conventional thermal conditioning systems.

The conventional heat treatment system (Figure 14) utilizes either a heat exchanger which produces an effluent WAS that is 22°C (40°F) below reactor temperature or a smaller one that produces an effluent 44°C (80°F) below reactor temperature. The procedure for calculating this heat shortage has been explained earlier. Direct steam is used to bring the sludge up to reactor temperature. The energy requirement for steam exceeds the energy available from digester gas, amounting to 1.8×10^{11} J for the system with the 22°C exchanger. The system with the 44°C exchanger requires 2.5 times more energy but capital cost is lower.

Thermal Pretreatment, Anaerobic Digestion System

Figure 15 presents energy balances for treatment systems when thermal conditioning is placed upstream of the anaerobic digesters. An immediate energy efficiency is the heat remaining in the thermal conditioned sludge which can be used to provide heat for subsequent digestion. Also, it has been proposed that since thermal conditioning will solubilize many organic solids, this could result in greater degradability and increased gas production in the digesters. Values used to derive digester gas production shown in Figure 15 are taken from results of this study. The volatile solids destruction and gas production values are presented in Tables 2, 7, and 19.

Anaerobic digestion following thermal conditioning was operated at thermophilic temperatues to make full use of the heat contained in the sludge and to improve the reaction kinetics in the digester. However, there is not sufficient heat in the thermal conditioned sludge to maintain digester temperatures if the heat exchangers provide a 22°C (40°F) temperature difference at the reactor. Using 24°C (75°F) as the temperature of the influent sludge, the treated sludge temperature upon discharge should be approximately 54°C (130°F). In order to provide the necessary 58,380 J/l (210 Btu/gal) to overcome digester heat losses, the influent sludge must be 63°C (145°F). Thus, the energy values in Figure 15 reflect this added energy demand. When the heat exchangers provide a 44°C (80°F) temperature difference, there is sufficient heat in the treated sludge to maintain digester temperatures.

The data presented in Figure 15 show that heat treatment and LPO conditioning of thickened WAS, followed by anaerobic digestion, both produce similar energy efficiencies. If the heat exchangers operate at a 22°C (40°F) temperature difference, both systems will yield surplus energy. However, both systems become net users of energy if the heat exchangers operate at a 44°C (80°F) temperature gradient. LPO conditioning of the primary - thickened WAS blend followed by anaerobic digestion will produce surplus energy at both heat exchanger efficiences.

Thermal Pretreatment - Anaerobic Treatment of Decant Liquors

Figure 16 presents energy balances for treatment systems when raw sludges are thermal conditioned, the solids separated by gravity for dewatering, and the decant liquors are treated by anaerobic processes. Two types of anaerobic treatment schemes are shown: anaerobic filtration and anaerobic digestion. These treatment schemes were pilot tested during this study and the results leading to the values are presented in Tables 9, 20, and 32. There is sufficient heat in the thermal conditioned decant liquors to maintain reactor temperatures in the anaerobic filter since the hydraulic detention times are four days or less.

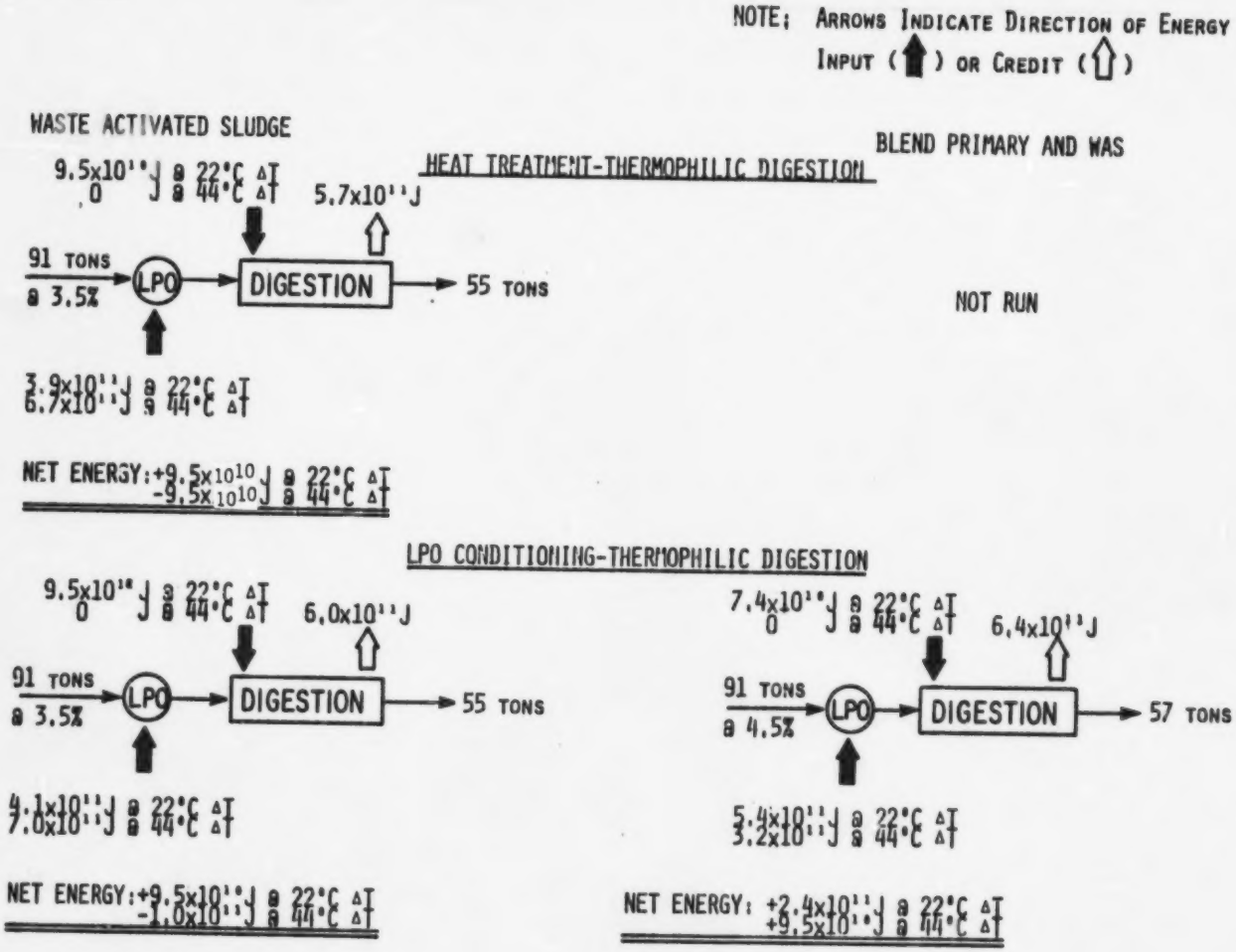


Figure 15. Energy balances for thermal pretreatment - anaerobic digestion systems

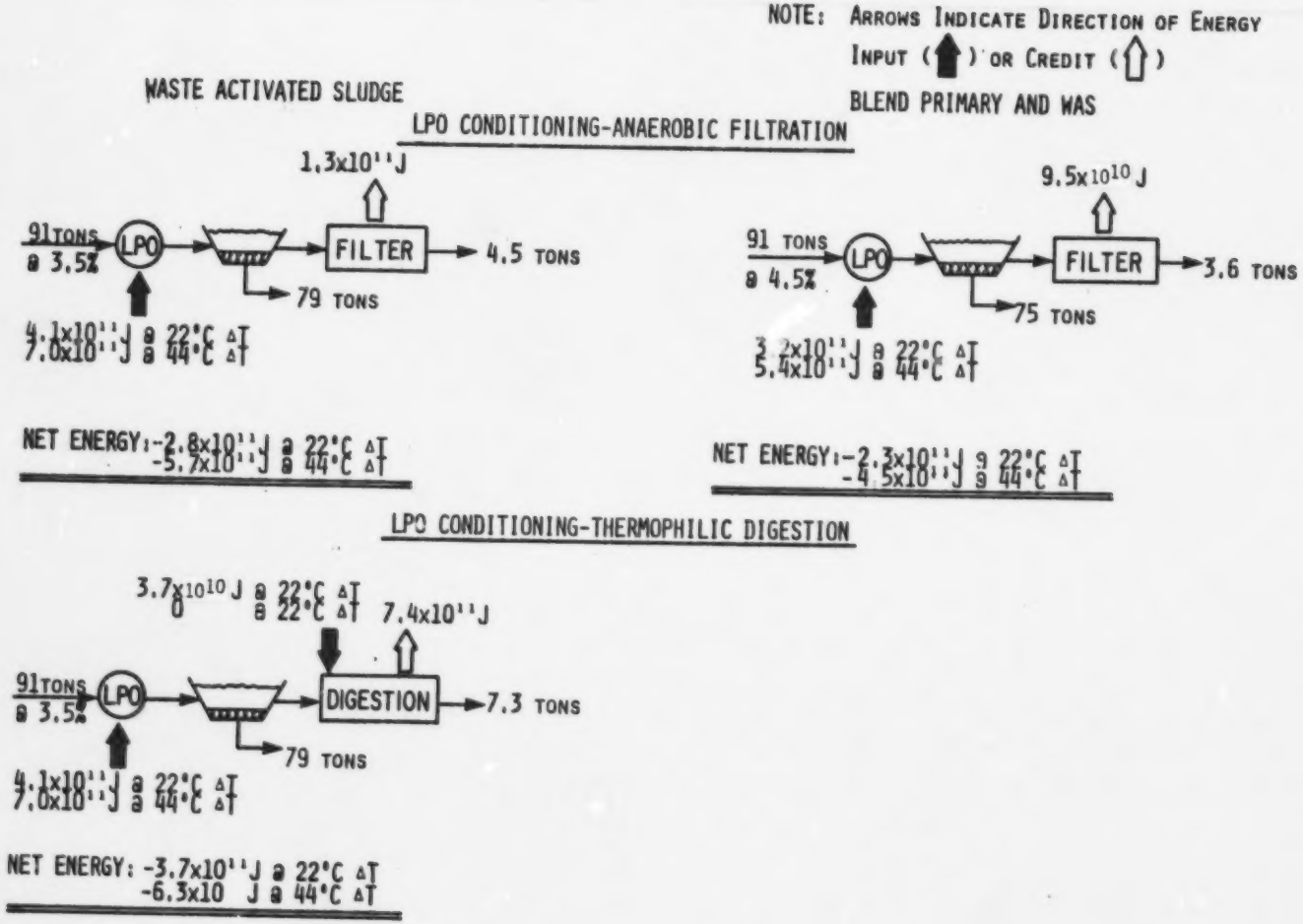


Figure 16. Energy balance for thermal pretreatment - anaerobic treatment of decant liquors.

The data in Figure 16 show that all treatment schemes are net users of energy. The reason for this outcome is that the gas produced from the anaerobic processes is not nearly sufficient to match the energy needed to operate the thermal conditioning unit. The least energy efficient system was the anaerobic digestion of the decant liquors at a 15-day hydraulic detention time. Apparently, much of the degradable organic material still remains associated with the solids fraction of the thermal conditioned sludge. No energy credit is given to this material since it is removed from the system prior to anaerobic treatment.

COMPARISON OF TREATMENT SYSTEMS

The net energy efficiency data from Figures 14, 15, and 16 are summarized in Table 40. The treatment systems are ranked in order of greatest efficiency to least efficiency. Table 40 also indicates the amount of sludge solids remaining for disposal after the thermal conditioning-anaerobic treatment process. Energy efficiencies for the top 9 ranked systems are presented graphically in Figure 17 for thickened WAS and in Figure 18 for the raw primary-thickened WAS blend.

The data indicates that treatment of raw primary and thickened WAS blend results in greater energy efficiency than does treatment of thickened WAS. Also, thermal treatment results in less net energy surplus when compared to sludge receiving just anaerobic digestion. If superior dewatering properties of thermal conditioning are necessary, it is more energy efficient to digest after thermal treatment rather than before thermal treatment. Heat treatment and LPO conditioning of thickened WAS followed by anaerobic digestion are equal in terms of energy efficiency as long as the heat exchanger temperature gradients are equal. The added electrical demands of the LPO conditioning system are offset by greater gas production during anaerobic digestion. The efficiency of the thermal conditioning heat exchangers can dramatically influence the energy balance; an energy producing system can become an energy demanding system if the heat recovery efficiencies are low. The thermal conditioning, gravity separation, anaerobic filtration systems are the least energy efficient and the least efficient in solids destruction.

TABLE 40. RANKING OF ENERGY BALANCES FOR VARIOUS THERMAL CONDITIONING SYSTEMS.

TREATMENT SYSTEM[1]	NET ENERGY 10^9 Joules (10^6 BTU)[1] ΔT = 22°C (40°F)	ΔT = 44°C (80°F)[2]	Tons of Solids Remaining for Disposal metric tons (short tons)
1. Digestion of Blend	427 (405)	427 (405)	64 (70)
2. LPO Conditioning - Digestion of Blend	243 (230)	95 (90)	57 (63)
3. Digestion of WAS	206 (195)	206 (195)	70 (77)
4. Digestion - Heat Treatment of Blend[3]	127 (120)	-95 (-90)	59 (65)
5. Digestion - LPO Conditioning of Blend[3]	106 (100)	-116 (-110)	57 (63)
6. Heat Treatment - Digestion of WAS	95 (90)	-95 (-90)	55 (61)
7. LPO Conditioning - Digestion of WAS	95 (90)	-100 (-95)	55 (61)
8. Digestion - Heat Treatment of WAS[3]	-179 (-170)	-464 (-440)	64 (70)
9. Digestion - LPO Conditioning of WAS[3]	-206 (-195)	-496 (-470)	65 (72)
10. LPO Conditioning - Anaerobic Filtration of Blend	-227 (-215)	-448 (-425)	79 (87)
11. LPO Conditioning - Anaerobic Filtration of WAS	-280 (-265)	-570 (-540)	83 (92)
12. LPO Conditioning - Anaerobic Digestion of WAS Decant Liquors	-353 (-335)	-628 (-595)	85 (94)

1. Basis is 100 M tons of sludge (dry solids) at 4.5 percent solids. Digestion or A.F. is at 35°C when it precedes thermal treatment and is at 50°C when it follows thermal treatment.
2. ΔT is the temperature approach in the countercurrent heat exchanger
3. These sequences were not carried out in this program. Mass remaining was estimated from thermal treatment results with raw sludges.

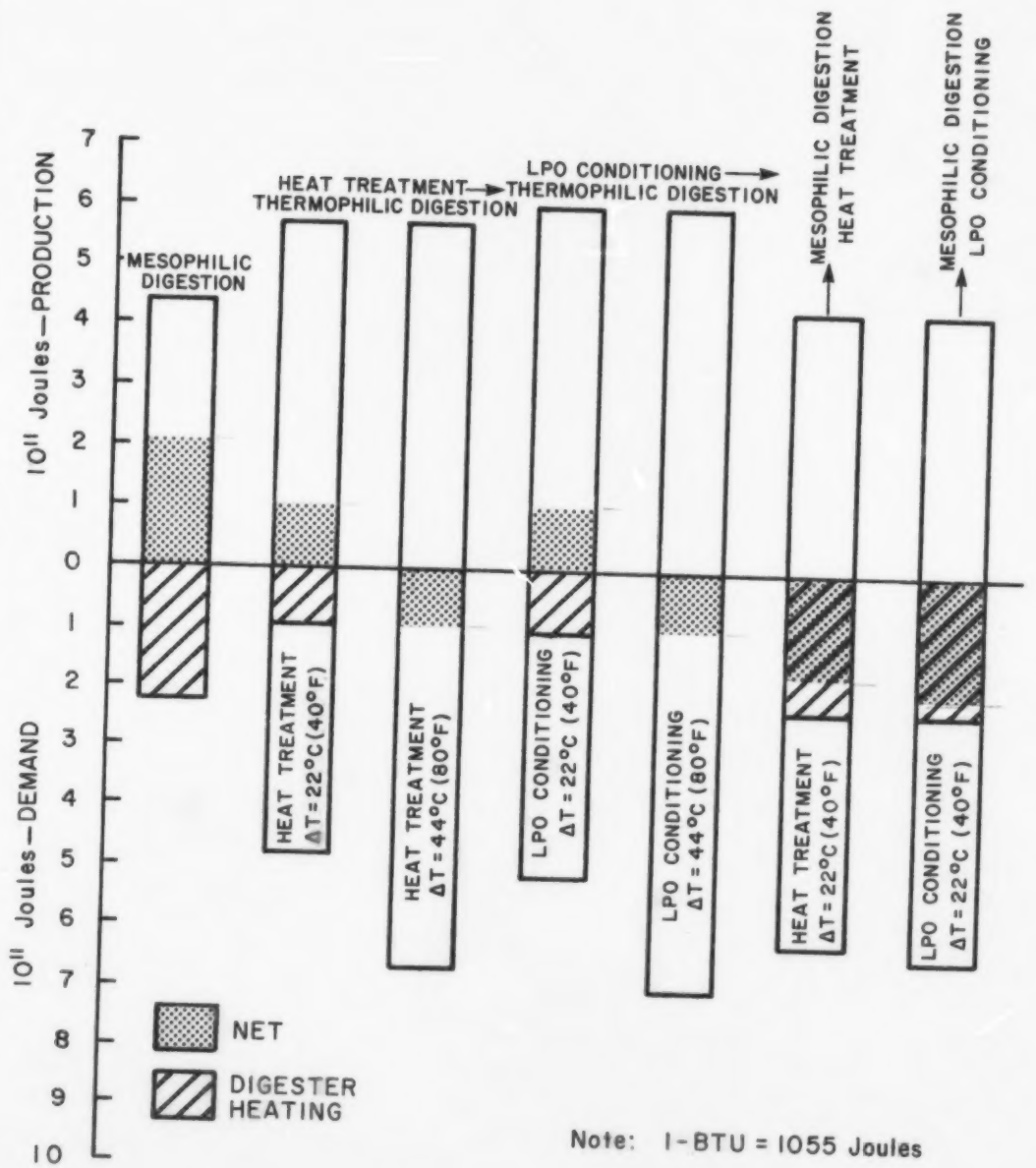


Figure 17. Comparison of energy requirements for thermal treatment of waste activated sludge

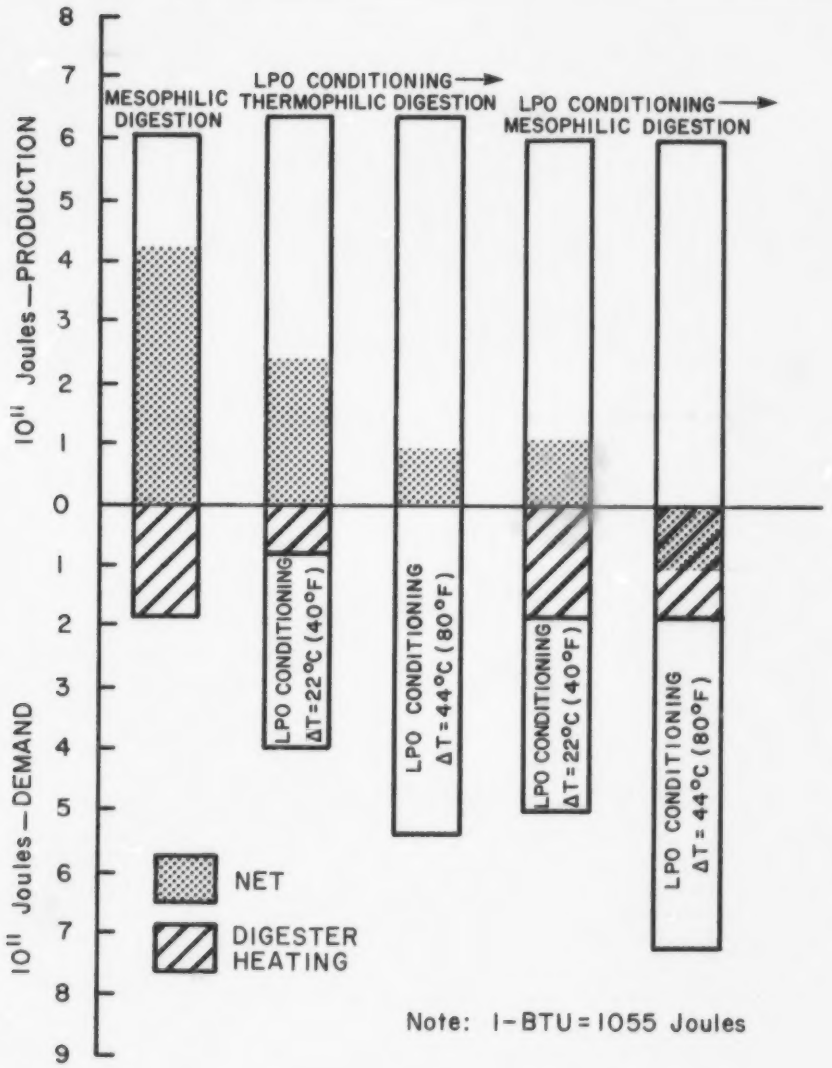


Figure 18. Comparison of energy requirements for thermal treatment of a primary and waste activated sludge blend.

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APPENDIX

COMPARATIVE SURVIVAL OF PATHOGENIC AND INDICATOR MICROORGANISMS IN THERMALLY TREATED AND NON-TREATED ANAEROBICALLY DIGESTED SLUDGE

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INTRODUCTION

The known presence of pathogens in sewage sludge raises questions regarding the possibility of infections among sewage workers and the general population who may be exposed to the sludge or sludge by-products. Epidemiological information is scant and contradictory (1). Sepp (9) and Burge (2) have reviewed the health aspects of applying sewage and sewage waste to land, and indicate that disease outbreaks have been associated with landspreading of raw wastes. Clark's (3) review of the literature relating to health hazards among sewage workers summarize the problems of interpreting the available data. Results were again contradictory and difficult to correlate.

Therefore, the knowledge that pathogens are present in sludge mandates a cautious approach to disposal alternatives. The relative effectiveness of methods of reducing or eliminating pathogens is an important consideration when evaluating disposal alternatives.

The pathogens usually found in sewage and sludge which are significant to human health can be classified into four basic groups: 1) the bacteria, 2) protozoan cysts, 3) helminth ova, and 4) viruses. The majority of the organisms found in raw sewage will concentrate in the sludge produced during standard wastewater treatment processes. Although a great variety of human pathogens may be introduced into the sewage of a community, the organisms of greatest concern are those known to be excreted in human feces.

The bacterial pathogen most commonly associated with sewage are the Salmonella and Shigella groups. Although some E. coli serotypes may be pathogenic under certain conditions, the large number of coliforms excreted with feces are usually not considered a direct public health threat; coliforms are used as indicators of the other more pathogenic enteric bacteria. Similarly, the fecal streptrococci, also found in high numbers in feces, are not usually considered pathogenic, but are tested for their indicator value. The Salmonella are found in high enough concentrations in sludge that their numbers may be directly determined. However, interpreting the significance of Salmonella data is often difficult because some controversy exists concerning the minimum dose of Salmonella in humans. Infective dose is the number of bacterial cells required to initiate an infection in an individual. This number will, of course, vary with the Salmonella serotype and the health and well-being of the individual. Traditionally, reports have indicated the infective dose of Salmonella to generally be quite high; i.e., on the order of magnitude of 10^4 to 10^5 cells. More recent information, however, indicates that infective doses may be as low as 10 to 100 cells (4, 7).

Another bacterial group excreted in feces, which may be of concern when considering sludge disposal alternatives, is the Mycobacteria, especially Mycobacteriaum tuberculosis. The tubercle bacilli, however, have not usually been considered during environmental studies due to the difficulty of working with these organisms in the laboratory. It is known that these organisms are highly resistant to disinfection and environmental stresses. Therefore, the Mycobacteria are still an unknown hazard potentially associated with sludge reuse.

Many different helminth and protozoan parasites may be found in sewage and sludge. Among these are the ova of Ascaris lumbricoides (human roundworm), Trichuris trichiura (whipworm), Ancylostoma and Necator (hookworm), and Hymenolepis (tapeworm). Cysts of Entamoeba histolytica are the most frequently observed protozoan form in sewage and sludge. Geographic factors affect the distribution of the various parasites; however, due to the ubiquitous nature of Ascaris, the ova of this parasite can be found in most locales.

When a human has "worms", the infection is probably due to the common intestinal roundworm, Ascaris lumbricoides. The life cycle of this parasite is well known. Infections are spread by the oral-fecal route. The life cycle starts with the fertilized egg being passed from the body of the female worm into the fecal material of the infected individual. The female Ascaris may reach a length of 20 to 35 cm (7.9 to 13.8 in) and produce as many as 200,000 eggs per day. The eggs are not embryonated when voided with the feces of the host. The embryo develops with the egg in the soil. Full embryonation requires approximately three weeks in a warm moist environment. When the eggs develop to larvae, they are infective to man.

The shell of an Ascaris ovum is highly resistant to chemicals and desiccation. The eggs will survive for weeks in 10% formalin. They are not affected by chlorine at doses as high as 10,000 mg/l. Ova used in the

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laboratory are stored in dilute H_2SO_4 solutions. This resistance enables the ova to survive and remain infective for years (10).

Ascaris ova are proposed as the parasite egg of choice for sludge monitoring and inactivation studies. The fact that they are widespread, highly resistant, and relatively easy to detect in sludge make these ova an ideal indicator for parasitic infections in general. The potential for parasitic disease transmission with land application of sludges has been thoroughly reviewed (6). The possibility of transmitting parasitic diseases should clearly be considered when planning management approaches to sludge disposal.

The potential for transmission of viral diseases through sludge reuse programs is probably the most poorly defined of the pathogen considerations. It is known that over 100 antigenic types of pathogenic viruses are excreted with fecal material. The best known of these is poliovirus. However, development of a vaccine effectively eliminated poliomyelitis as a major public health concern. Currently, the most important virus-related infectious agent that is associated with sewage is the agent of hepatitis; the other enteric viruses are often the etiologic agents of many nonspecific diseases and infections.

The organic material in sewage appears to have a protective effect on viruses, helping to provide some defense against various environmental stresses (8). It is also well established that viruses adsorb to the solids in sewage (13), so it is not surprising that large numbers of viruses have been found in sewage sludges.

Other research has indicated that anaerobic digestion may effectively reduce virus levels and that ammonia produced in digesters is virucidal (5, 12). However, the authors' laboratory and others have routinely isolated enteric viruses from anaerobically digested sludge (7). Therefore, it is prudent to assess the virus inactivating efficiency of sludge handling methods and to evaluate the fate of viruses when developing sludge disposal alternatives. Thermal pretreatment of sludge is designed to increase digestibility and improve dewatering characteristics. Destruction of pathogens is an additional potential benefit which may be derived from heating the sludge. Samples have been collected since January 1977, in order to assess the effectiveness of the Zimpro sludge conditioning equipment for pathogen removal. This report describes the results of the microbiological evaluation.

MATERIALS AND METHODS

Bacteria

Measured samples were placed in a Waring blender jar and an appropriate amount of Tween 80 was added to make a 0.1% solution. The mixture was blended for one or two minutes in order to produce a pipetable, well-mixed suspension. Lauryl tryptose broth and azide dextrose broth were

inoculated for multiple tube dilution tests for total and fecal coliforms and fecal strep, respectively. The tests were performed according to Standard Methods, 14th edition.

In addition, tetrathionate broth was inoculated for a multiple tube dilution test for Salmonella. After 18 to 24-hr incubation at 37°C (99°F), the tetrathionate cultures were streaked to bismuth sulfite agar and XLD agar. The plates were incubated for 24 hr at 37°C (99°F) and then examined for colonies exhibiting typical Salmonella morphology. Potential Salmonella colonies were picked and inoculated into TSI agar slants. The TSI slants showing Salmonella reactions after 24-hr incubation at 37°C (99°F) were confirmed with polyvalent O antisera. The tetrathionate broth tubes which had been shown to contain Salmonella were then used to compute a MPN value.

Ascaris Ova

The remainder of the blended sample that was prepared for the bacterial tests (plus additional blended sample, if necessary), was washed through a 48-mesh Tyler sieve. The resulting suspensions were allowed to settle overnight. The supernatant was decanted and the ova in the sediment were concentrated using a $ZnSO_4$ density gradient flotation procedure. The concentrated ova were then enumerated using a Sedgwick-Rafter cell and viability of the ova were determined using Nile blue sulfate.

Viruses

Beef extract (BE) was weighed into the liquid digested sludge sample to bring the concentration to 3% weight/volume. The BE-sludge solution was maintained at pH 7 and sonicated for two minutes. The solids were then removed by centrifugation. Viruses eluted into the BE supernatant were concentrated by adjusting the supernatant to pH 3.5 with 6N HCl, added dropwise. After 30-min mixing, the resulting precipitate was collected by centrifugation and redissolved in a small volume of phosphate buffer. Plaque assays were performed using Buffalo Green Monkey Kidney cells. Concentrates were inoculated in 25-cm^2 (3.9-in^2) assay flasks and observed for plaques for a period of two weeks or until the controls died. It was necessary to dilute the concentrates in order to eliminate toxicity problems during the assay.

RESULTS AND CONCLUSIONS

The sampling points for this study were as follows:

1. Stabilization Influent - Raw undigested sludge
2. Heatrate - Raw sludge following the Zimpro thermal conditioning process

3. Stabilization Effluent - The thermally conditioned sludge after anaerobic digestion

4. Research Digester Sludge - Anaerobically digested sludge, no conditioning before digestion

Tables A-1 through A-3 summarize the laboratory data from this study. Interpreting the results, however, presented some difficulties. Figure A-1 depicts the data pattern for total coliform during the evaluation. The influent shows a fairly consistent level of coliforms with the average, approximately 10^8 MPN/100 ml. With the exception of one data point, the coliform results for the stabilization effluent stayed within plus or minus 1.5 log of the average. Results for the research digester (not shown in Figure A-1) were also consistent, averaging 10^7 MPN/100 ml. The heatrate samples, as seen in Figure A-1, fluctuated greatly, ranging from <3 to $>10^6$ MPN/100 ml. This large variation could not be explained, especially considering the high temperatures the sludges were exposed to during thermal treatment. The apparent discrepancy was discussed with the project engineer, and it was decided that sampling difficulties could account for the observed variations. Regrowth may have occurred during the time between thermal treatment and sample collection.

The pathogen analyses did not suffer from the problems seen with the indicator bacteria. Figure A-2 illustrates the data points for Salmonella. It can be seen that the Salmonella in the heatrate were consistently very low or below test detection limits. Figure A-3 shows the average concentration for each bacterial group at each of the sampling points. In spite of the problems with the indicator bacteria, it is still clearly visible that thermal pretreatment caused significant reductions of the bacterial groups in the stabilized effluent compared to the standard digester effluent. The effect of the thermal treatment is most apparent with the Salmonella, although some regrowth did occur in the digester. Nevertheless, Salmonella concentrations still remained lower than those in the untreated, digested sludge.

Data for the parasitic helminth ova were easier to interpret. The individual Ascaris results are summarized in Table A-1, and the average reduction of ova at each sampling point is shown in Table A-2. Viable ova were detected only once in a heatrate or stabilization effluent sample, whereas viable ova were detected in every research digester sample. No regrowth can occur with the helminth ova; the thermal treatment was, therefore, a decidedly effective means of eliminating any parasite-related health problems which might be associated with sludge reuse.

The virus results shown in Table A-3 are somewhat inconclusive. Within the framework of the project, a relatively smaller virus data base was obtained, adding to the difficulty of interpretation of results. Viruses were isolated in all eight influent samples, indicating the virus elution and concentration procedure was effective. Previous experimental work with polio-virus Type 1 (Chat) seeded sludges indicated the method was capable of yielding approximately 35% recovery with a 40-fold concentration factor. Also worth noting is the increase in the virus titer of the

TABLE A-1. MICROORGANISM SUMMARY FOR THERMALLY PRETREATED WAS

Date 1977	Sample	Indicator Bacteria MPN/100 ml				Ascaris ova per 100ml	
		Total Coliform	Fecal Coliform	Fecal Strep.	Salmonella sp.	Total	Viable
1-20	Influent	2.3×10^8	4.3×10^7	ND	4×10^3	65	39
	Heatrate	1.5×10^3	7.5×10^2	ND	<1	7	1
	Stab. Eff.	43	43	ND	<1	< 0.3	< 0.3
2-02	Influent	7.5×10^8	2.0×10^8	ND	9.3×10^4	11	7
	Heatrate	2.1×10^7	6.4×10^6	ND	<1	13	< 2
	Stab. Eff.	43	43	ND	<1	6	< 6
	Dig. Eff.	2.9×10^7	6.4×10^6	ND	2.3×10^2	5	5
2-17	Influent	4.3×10^8	4.3×10^7	ND	3.9×10^3	66	66
	Heatrate	2.3×10^6	1.5×10^5	ND	<1	<2	< 2
	Stab. Eff.	7.5×10^3	3.9×10^3	ND	<1	10	< 1
	Dig. Eff.	2.3×10^7	9.3×10^6	ND	4.3×10^2	25	8
3-02	Influent	2.3×10^8	2.3×10^7	ND	2×10^3	9	5
	Heatrate	1.5×10^7	4.3×10^4	ND	<1	2	< 1
	Stab. Eff.	2.3×10^6	9.3×10^5	ND	4.3×10^2	3	< 1
	Dig. Eff.	4.3×10^6	4.3×10^6	ND	2.0×10^2	19	5
3-17	Influent	4.3×10^8	9.3×10^7	ND	1.1×10^3	9	< 5
	Heatrate	2.3×10^2	9	ND	<1	3	< 0.8
	Stab. Eff.	3.3×10^4	2.3×10^4	ND	2.3×10^2	2	2
	Dig. Eff.	9.3×10^7	3.3×10^6	ND	2.8×10^1	28	14
3-30	Influent	2.0×10^8	4.3×10^7	ND	2.3×10^5	10	7
	Heatrate	<3	<3	ND	<3	3	< 2
	Stab. Eff.	9	4	ND	<1	1	< 0.7
	Dig. Eff.	4.3×10^6	9.3×10^5	ND	1.4×10^2	3	3
4-13	Influent	9.3×10^8	2.3×10^7	ND	2.1×10^3	32	32
	Heatrate	4.6×10^5	4.3×10^4	ND	4	1	< 0.5
	Stab. Eff.	43	<3	ND	<1	0.5	< 0.5
	Dig. Eff.	2.4×10^8	4.6×10^7	ND	4	12	12

ND - Not Determined

TABLE A-1 (continued).

Date 1977	Sample	Indicator Bacteria MPN/100 ml				Ascaris ova per 100 ml	
		Total Coliform	Fecal Coliform	Fecal Step.	Salmonella sp.	Total	Viable
4-27	Influent	9.3×10^3	9.3×10^8	3.9×10^6	ND	ND	-
	Heatrate	< 3	<3	<3	ND	ND	-
	Stab. Eff.	23	4	2.3×10^3	ND	ND	-
	Dig. Eff.	9.3×10^7	7.5×10^6	1.5×10^5	ND	ND	-
5-11	Influent	2.4×10^9	4.3×10^8	2.3×10^6	2.3×10^4	25	19
	Heatrate	9.3×10^2	9.3×10^2	23	<1	5	<2
	Stab. Eff.	23	23	2.3×10^2	<1	1	<1
	Dig. Eff.	9.3×10^5	2.3×10^5	4.3×10^4	15	18	5
5-25	Influent	4.6×10^9	4.3×10^8	7.5×10^6	ND	ND	-
	Heatrate	<3	<3	43	ND	ND	-
	Stab. Eff.	23	4	230	ND	ND	-
6-22	Influent	1.5×10^8	7.5×10^7	9.3×10^5	2.1×10^1	26	26
	Heatrate	9.3×10^3	2.3×10^3	4.3×10^2	-	10	<2.5
	Stab. Eff.	4.3×10^2	2.3×10^2	4.3×10^2	7	10	<2.5
7-07	Influent	2.4×10^9	4.3×10^8	2.4×10^7	7	25	17
	Heatrate	2.3×10^6	2.3×10^3	4.3×10^3	<1	5	<0.1
	Stab. Eff.	2.3×10^3	2.3×10^1	2.3×10^2	<1	5	<0.1
7-22	Influent	2.4×10^7	2.4×10^7	2.4×10^6	ND	ND	-
	Heatrate	2.4×10^4	9.3×10^3	2.4×10^3	ND	ND	-
	Stab. Eff.	2.4×10^2	2.4×10^2	7.5×10^2	ND	ND	-
7-27	Influent	1.4×10^7	1.4×10^7	9.3×10^6	ND	ND	-
	Heatrate	1.1×10^6	1.1×10^6	2.4×10^2	ND	ND	-
	Stab. Eff.	4.6×10^4	4.6×10^4	$\geq 2.4 \times 10^5$	ND	ND	-
8-10	Influent	2.4×10^8	2.4×10^8	4.3×10^6	9.3×10^3	ND	-
	Heatrate	9.3×10^4	4.3×10^4	4.6×10^4	<1	ND	-
	Stab. Eff.	9.3×10^2	9.3×10^2	7.5×10^2	<1	ND	-

ND - Not Determined

TABLE A-2. PERCENT REDUCTION OF TOTAL AND VIABLE ASCARIS OVA FROM THERMALLY TREATED VERSUS NON-TREATED SLUDGE

Sample	Reduction of Ascaris Ova *	
	Total	Viable
Heatrate	≥82%	≥94%
Stabilization Effluent	≥86%	≥93%
Digester Effluent	46%	66%

* Influent Baseline

TABLE A-3. VIRUS DATA FROM THERMALLY CONDITIONED WAS

Sample	Plaque Forming Units per Liter (1977)							
	1-20	2-17	3-17	4-13	5-11	6-23	7-07	8-10
Stabilization Influent	70	100	140	175	385	525	910	1645
Heatrate	<35	<35	<35	<35	<35	<35	<35	35
Stabilization Effluent	<35	<70	<35	210	<35	<35	<35	70
Digester Effluent	ND	<70	<70	<35	35	ND	ND	ND

influent samples from the January level of 70 per liter to the August high of 1645 per liter. It has frequently been reported that enteric virus titers increase in sewage during the warm summer months and usually peak between late summer and early fall (11). The influent virus data summarized in Table A-3 clearly reflects this observation.

Significant virus reduction occurred during the treatment processes. However, virus removal was not any better in the thermally treated digestion process than it was in the standard digestion process, as illustrated in Figure A-4. This result was not anticipated because the temperature the sludge was exposed to during thermal treatment would be expected to cause complete destruction of viruses. Like the parasite ova, the enteric viruses also are not capable of regrowing in the sludge. Therefore, the virus isolations in thermally treated samples must be due to one, or a combination, of three possible situations.

1. All of the sludge was not uniformly heated to the reported temperature during the thermal treatment;

2. Contamination of the sample occurred in the field after thermal treatment; or

3. Contamination of the sample occurred in the laboratory during concentration and assay.

There is no evidence available to the authors, at this time, to favor one possible explanation over the others.

SUMMARY

Thermal pretreatment of sludge was shown to effectively reduce pathogen populations. Viable parasitic helminth ova were essentially eliminated from the sludge. Although it was demonstrated that bacterial concentrations could be reduced as much as eight logs, subsequent regrowth apparently minimized the positive effects of the thermal treatment. Virus results were somewhat enigmatic: significant reductions were achieved, but the questions posed concerning virus survival will only be answered through continued study.

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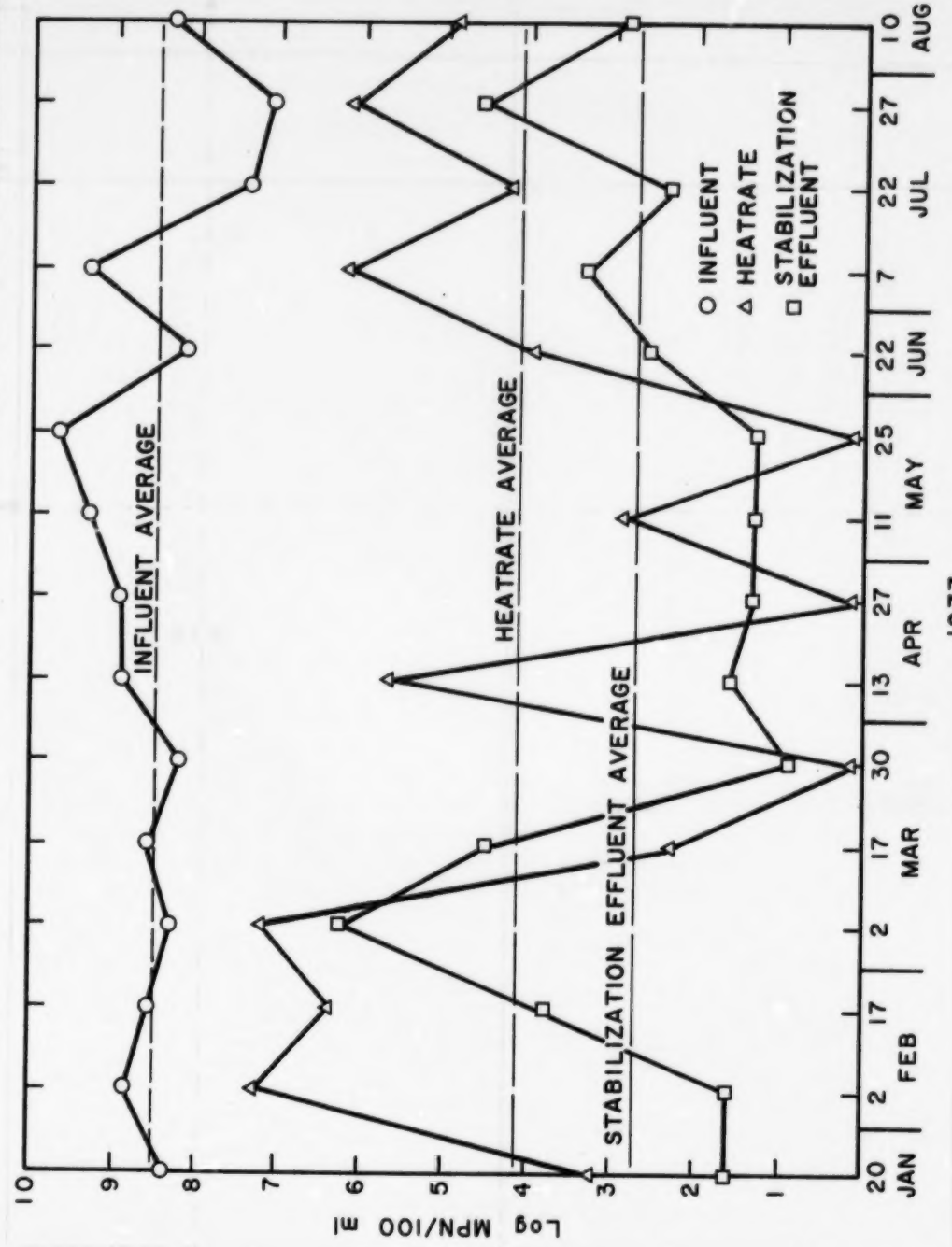


Figure A-1. Summary total coliform data for thermally conditioned WAS.

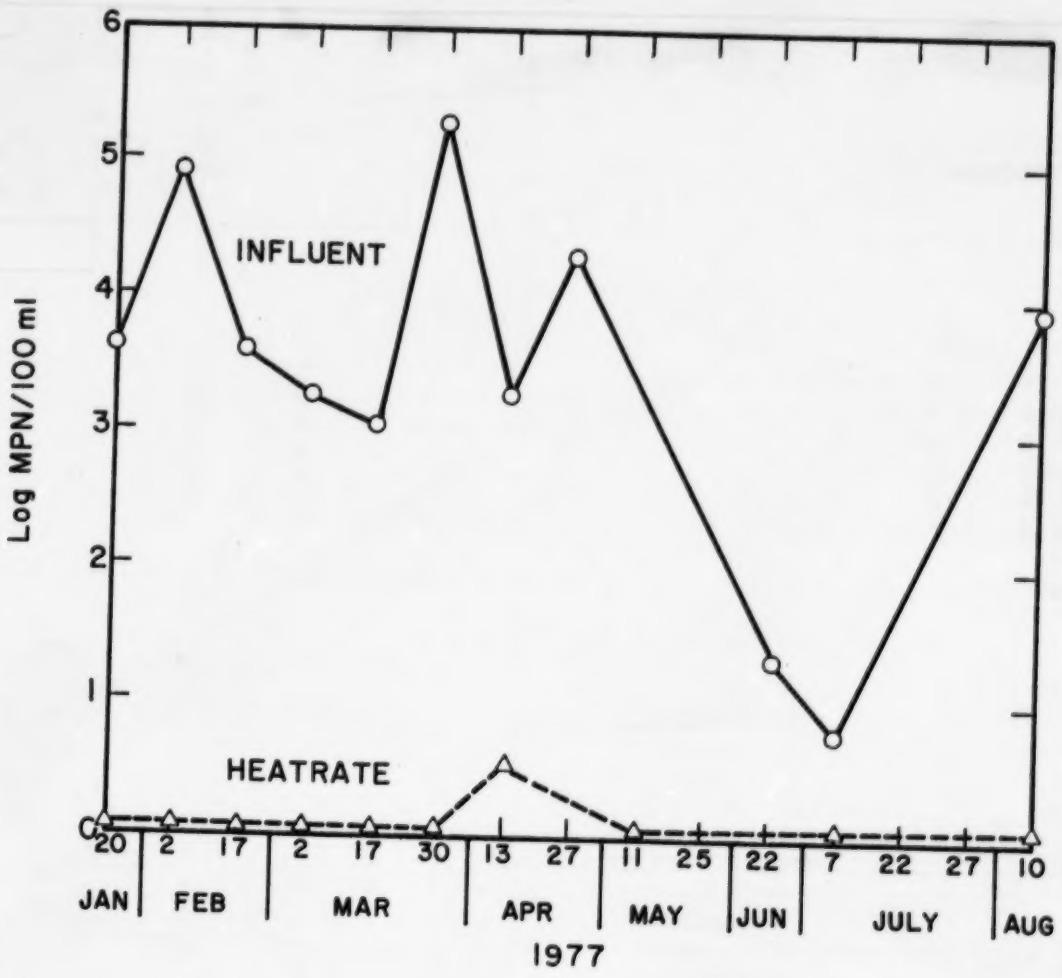


Figure A-2. Summary of Salmonella sp. data for thermally conditioned WAS

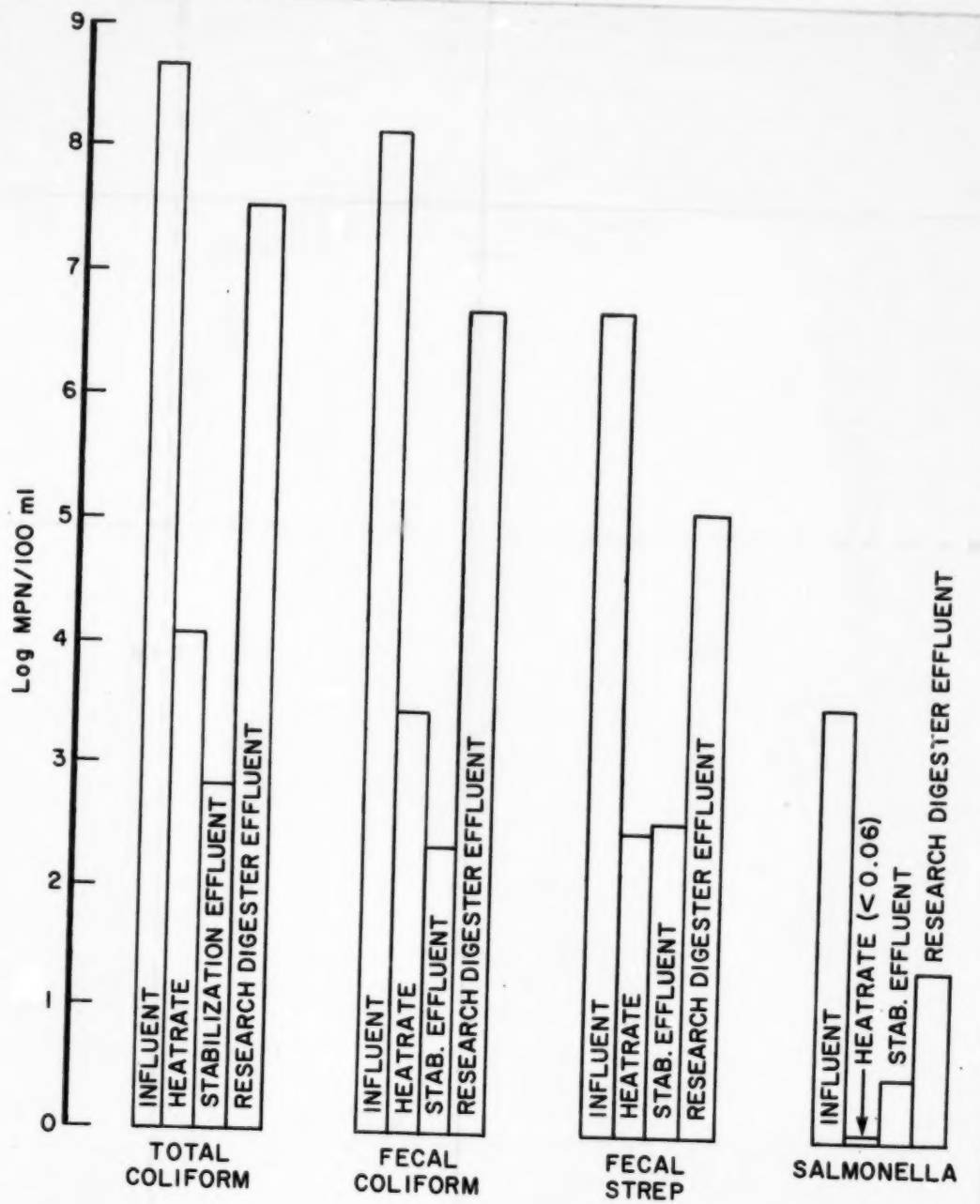


Figure A-3. Average bacterial concentrations of thermally conditioned WAS.

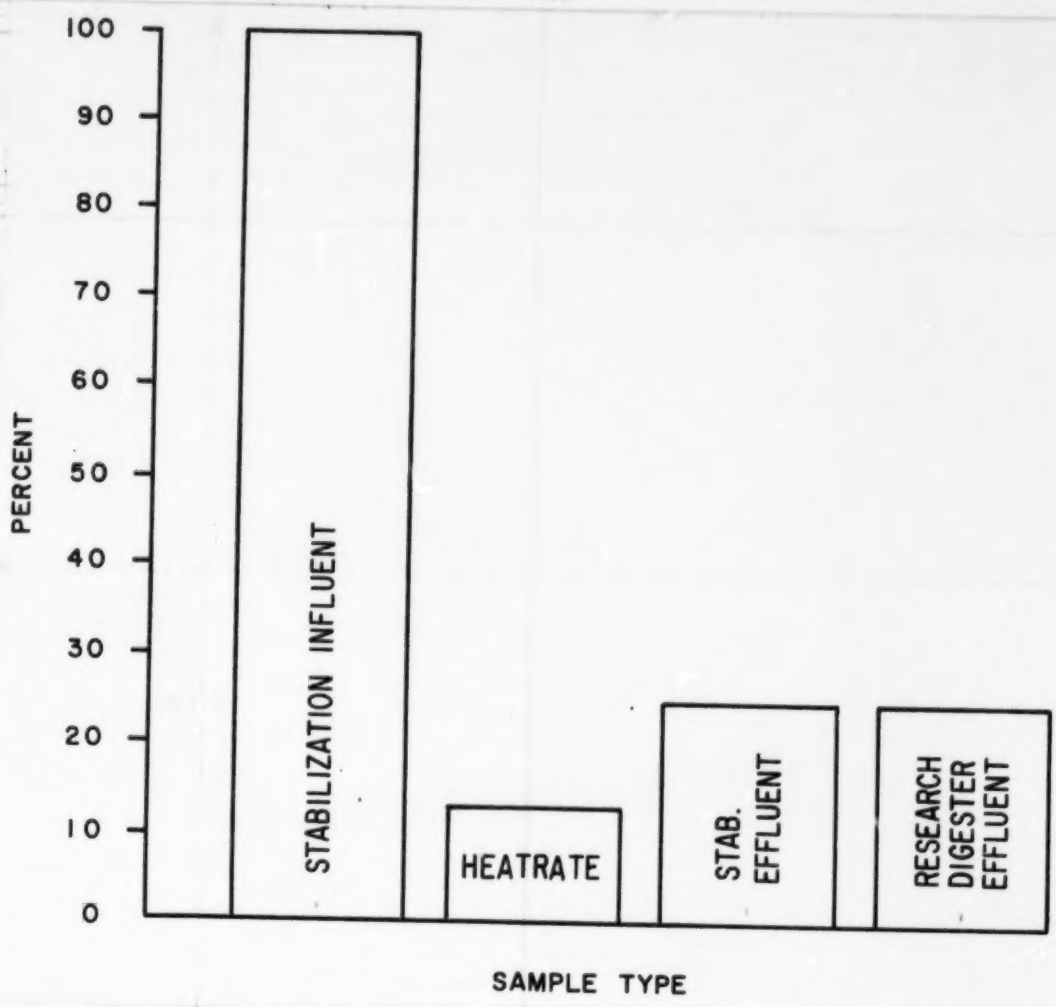


Figure A-4. Percent samples yielding positive virus isolations.

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